

Introduction to Fast Ignition



Nuclear Astrophysics Workshop

Livermore, CA

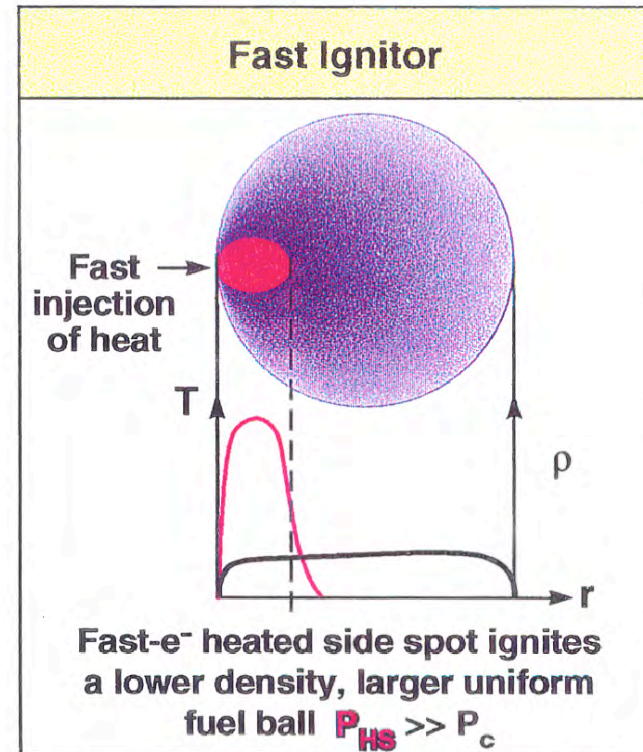
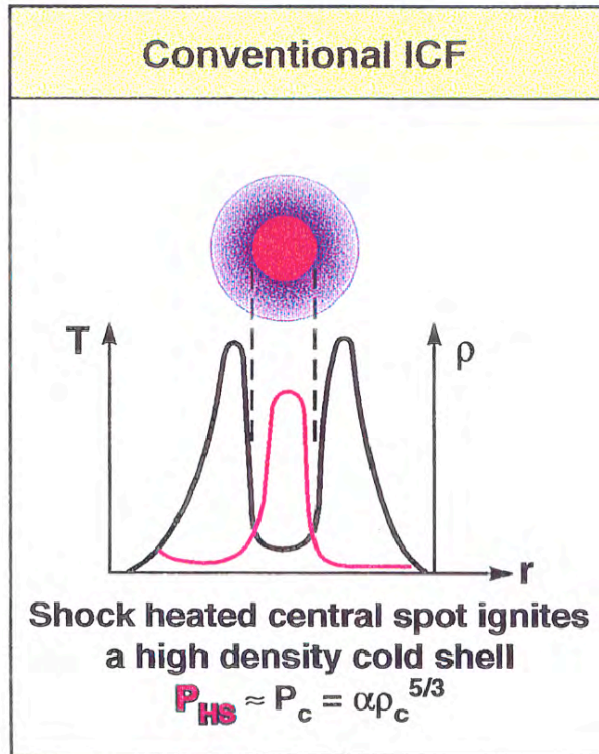
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Technology advances had made innovative concepts possible: ultra-high brightness lasers may allow a fundamentally new method of igniting inertial fusion capsules



* Tabak, Hammer, Glinsky, Kruer, Wilks, Woodworth, Campbell, & Perry *Phys. Plasmas* **1**, 1626 (1994).

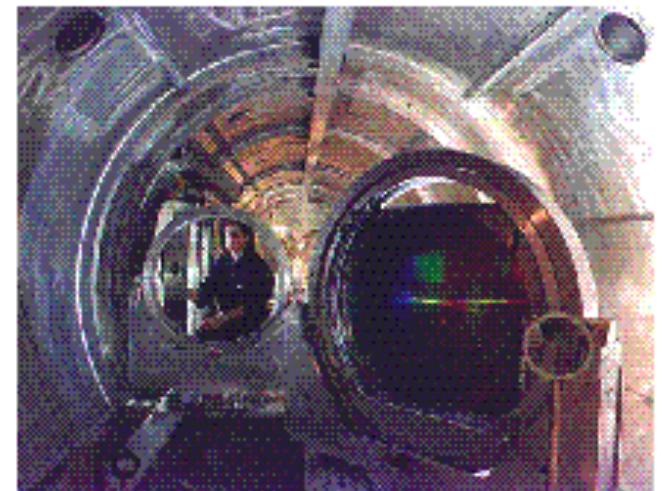
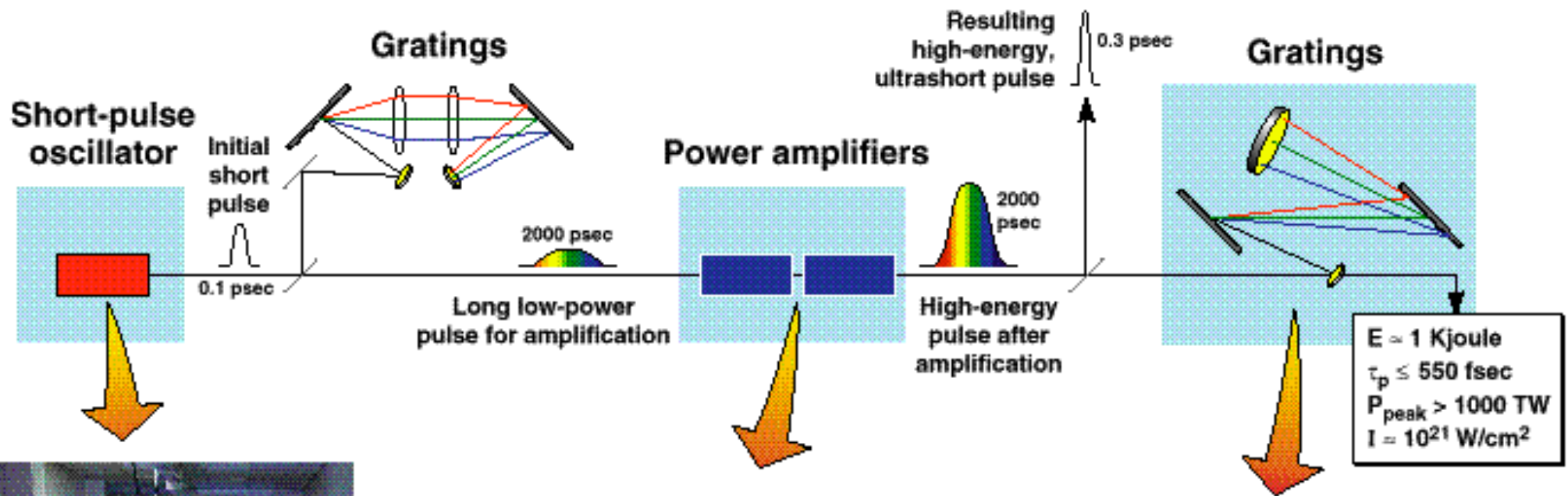
** H. Azechi et al., *Laser Part. Beams* **9**, 2 (1991).

Advantages of Fast Ignitor

- Fast Ignitor implosions are less stressing: (mix, convergence, ...)
- Lower $\rho \Rightarrow$ more mass to burn ($E_c \approx \alpha M_c \rho_c^{2/3}$) \Rightarrow Higher Gain

Significant R&D is required to explore potential of this concept

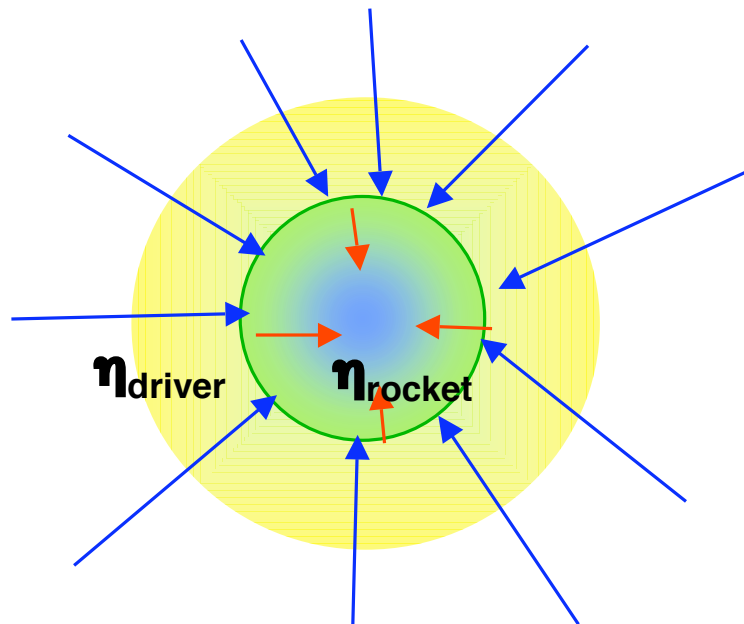
Chirped pulse amplification(CPA) and recompression increase power by 10^3 - 10^4



Fast Ignition entails the assembly of compressed fuel followed by fast heating

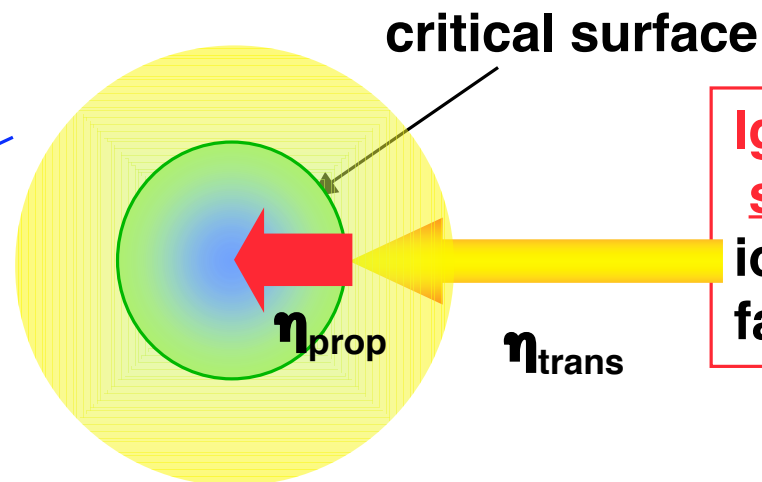


1. Compress fuel
with implosion



Compression
driver:
Laser
Ion beam
Z-pinch

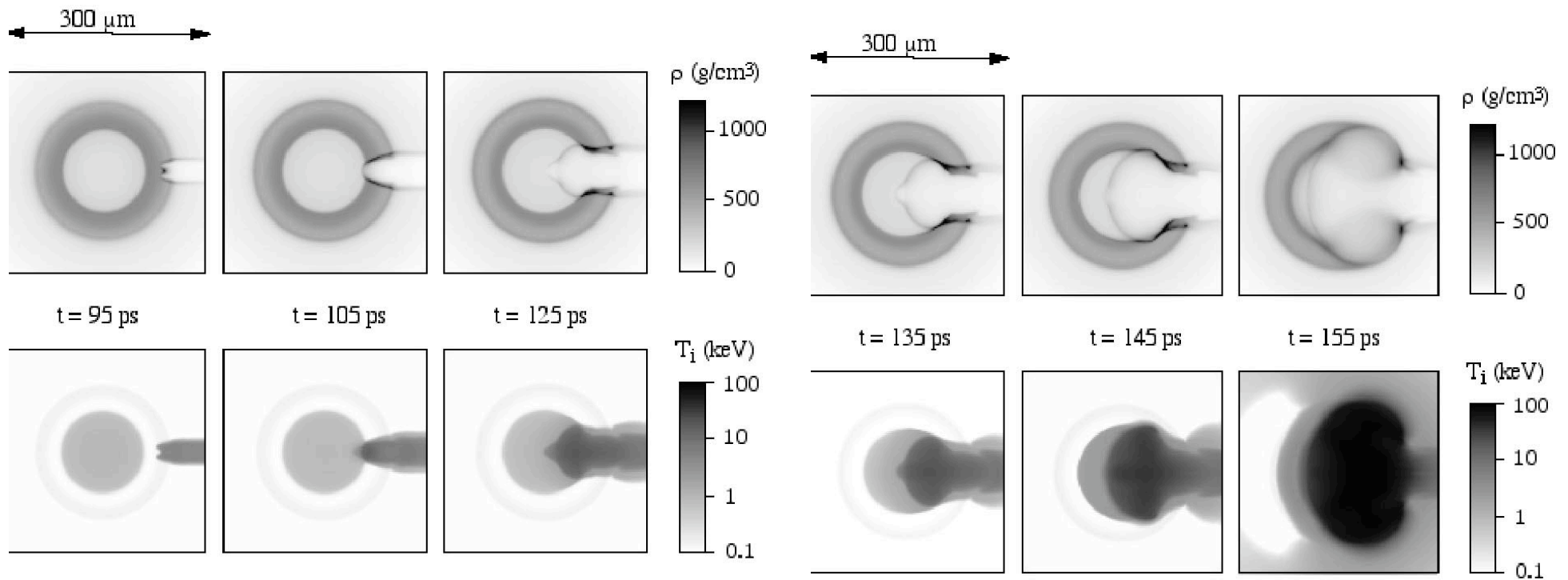
2. Ignite fuel



Ignition driver:
short pulse laser
ion beam
fast fluids

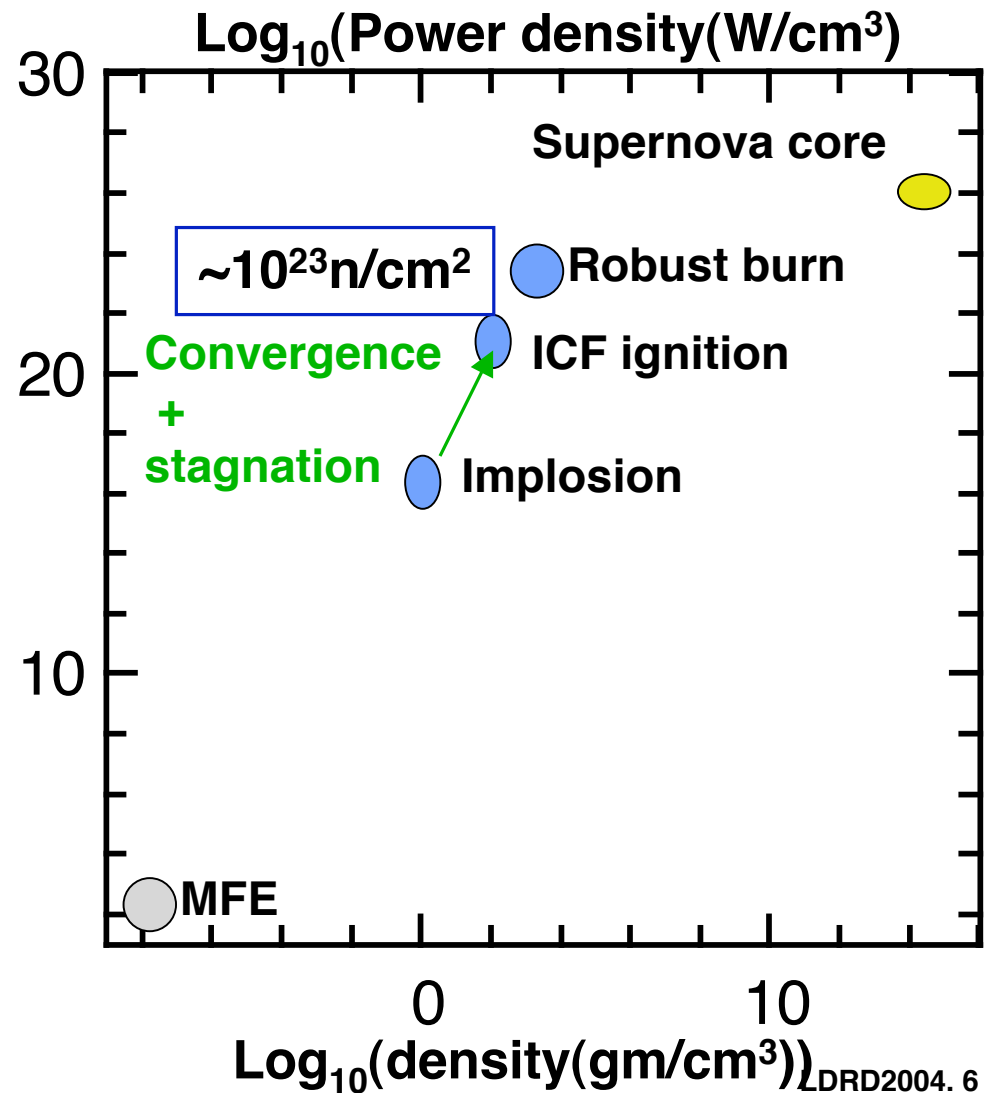
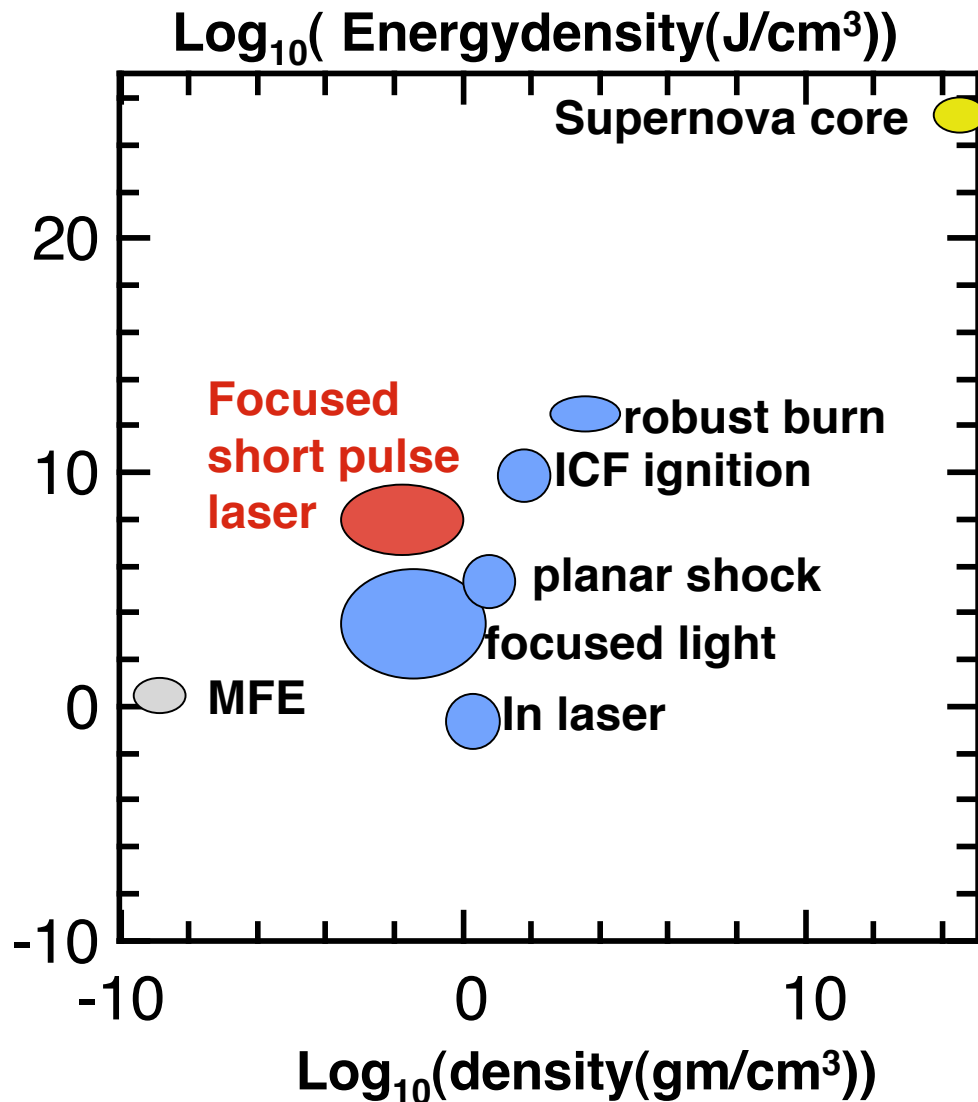


Proton heated targets show ignition* starting at surface and propagating

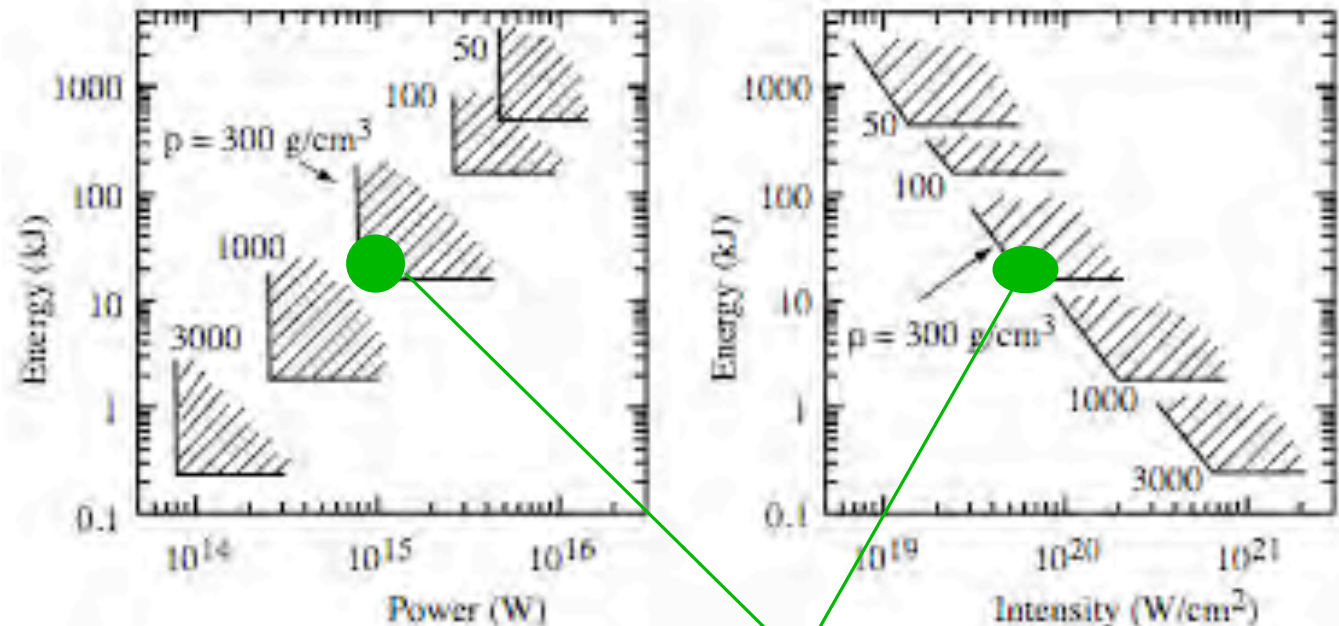
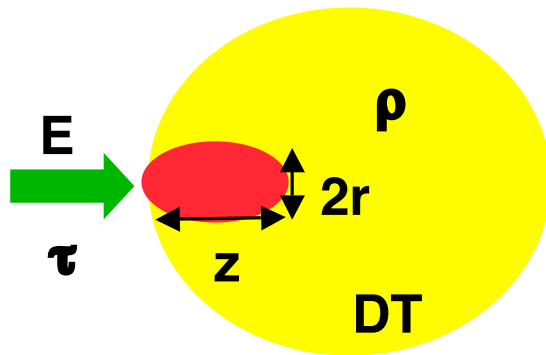


*Atzeni and coworkers

ICF ignition requires large energy and power densities



Atzeni and coworkers found Fast Ignition requirements using numerical simulations



Ignition criteria:

$T=12 \text{ keV}$, $\rho R=0.6 \text{ g/cm}^2$

$E_{\text{ign}}(\text{kJ})=140(\rho/(100 \text{ g/cm}^3))^{-1.85}$

$\rho=300 \text{ gm/cc}$

$E=18 \text{ kJ}$

$P=0.9 \text{ PW}$

$\Rightarrow \tau=20 \text{ ps}$

$I=6.8 \cdot 10^{19} \text{ W/cm}^2 \Rightarrow r=20 \text{ } \mu\text{m}$

Conflicting heating and compression requirements determine gain curves



Why is there a non-trivial energy requirement to achieve ignition and burn?

Little energy is required to assemble enough fuel to bootstrap and achieve high gain

$$E_{\text{comp}} \propto M_c \rho_c^{2/3}$$

Vanishes for $\rho_c = \rho_{\text{solid}}$

Little energy is required to heat bootstrap region to ignition temperature

$$E_{\text{hotspot}} \propto (\rho R)_{\text{HS}}^3 T / \rho_{\text{HS}}^2$$

Vanishes for $\rho \rightarrow \infty$ for fixed ρR

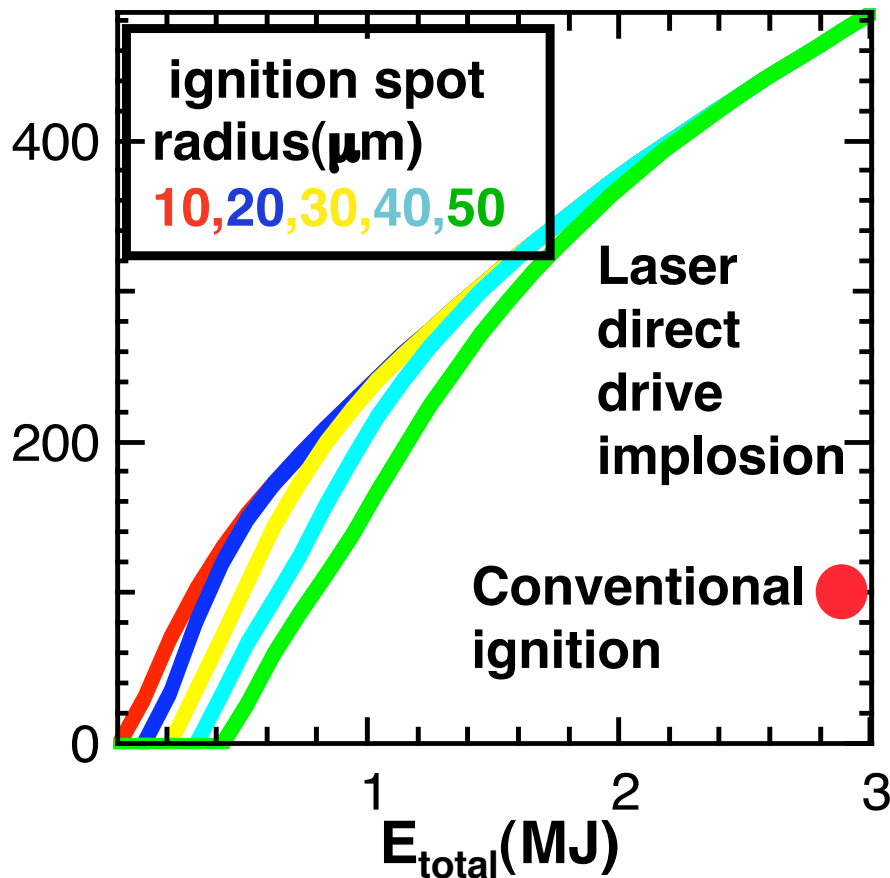
Want to maximize $\phi M (/E_{\text{tot}})$ including both energies
 $\phi = \rho R / (\rho R + 6)$

What are possible relations between hotspot and mainfuel?

Isochoric \Rightarrow uniform density (and huge pressure jump)

Isobaric \Rightarrow uniform pressure (and low density hotspot)

This simple model shows how gain depends on a number of performance parameters



Nominal model:

$$\eta_{\text{ign}} = 0.25$$

$$e^- \text{ range}(\text{g/cm}^2) = 0.6 I_{19}^{1/2}$$

$$\lambda_{\text{comp laser}} = 0.33 \mu\text{m}$$

For gain =100

Parameter	$E_{\text{total}}(\text{MJ})$
Nominal model	0.3
$E_{\text{ign}} \times 1/2$	0.1
$\eta_{\text{ign}} \times 0.25$	1.7
$\eta_{\text{hydro}} \times 0.5$	0.95
$\text{range}_{\text{ign}} \times 3$	0.75
0.5 μm drive	0.55

Gain above 100 can be traded to relax system constraints:

Low tritium fuel

Relaxed driver constraints

What design and physics issues will determine these gain curves?

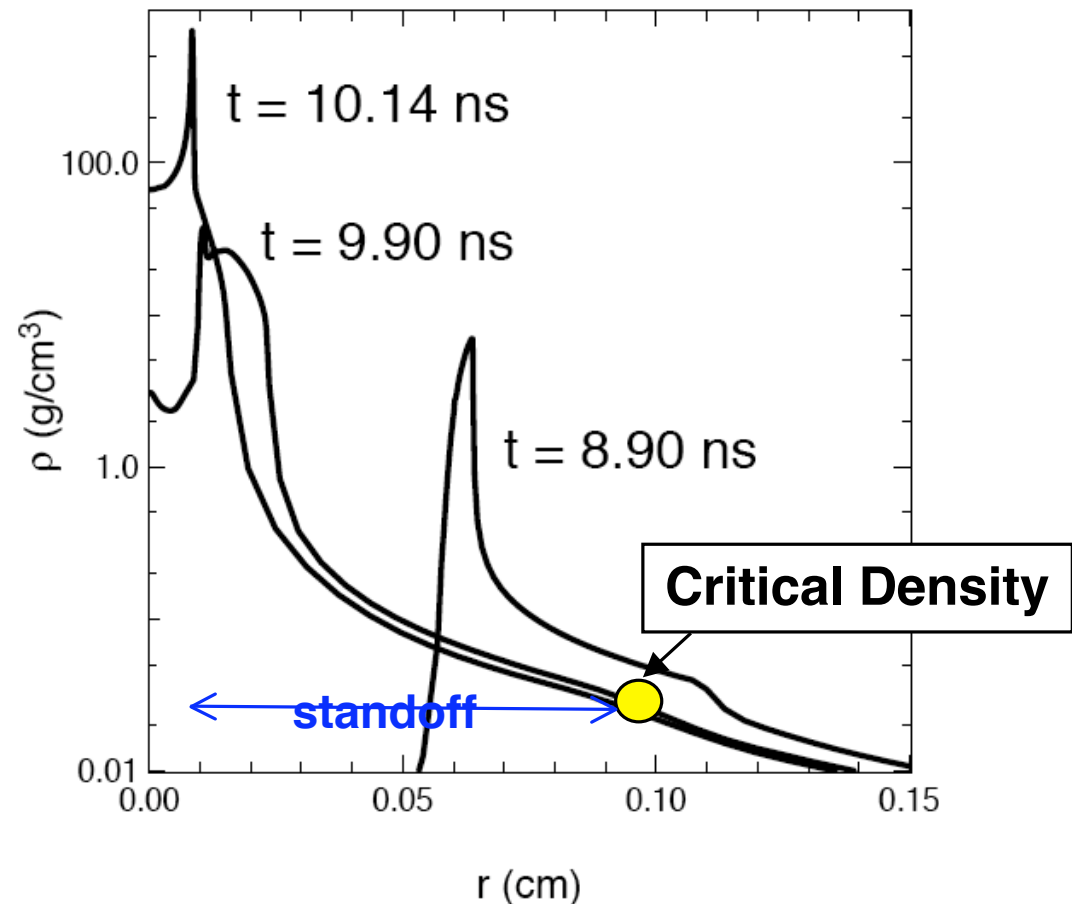


- How to assemble fuel
 - Efficiently produce high density fuel without low density center
- How to couple energy to fuel
 - Laser transport(**get energy close to fuel**)
 - Filamentation and hole boring(transport can spread and absorb laser energy)
 - Cone focus geometries
 - Asymmetric implosions
 - Other ideas
 - Laser plasma interaction and coupling efficiency(**make hot e^- with what phase space distribution**)
 - Electron transport(**deliver energy from critical surface to fuel**)
 - Multiple scattering plasma instabilities
 - Proton generation and transport(**efficiency, brightness, shorting out, multiple scattering, long pulse behavior**)

An implosion is required to assemble the fuel but produces difficulties that need to be overcome



The low density core leads to low burn efficiency and more difficult fast ignition.

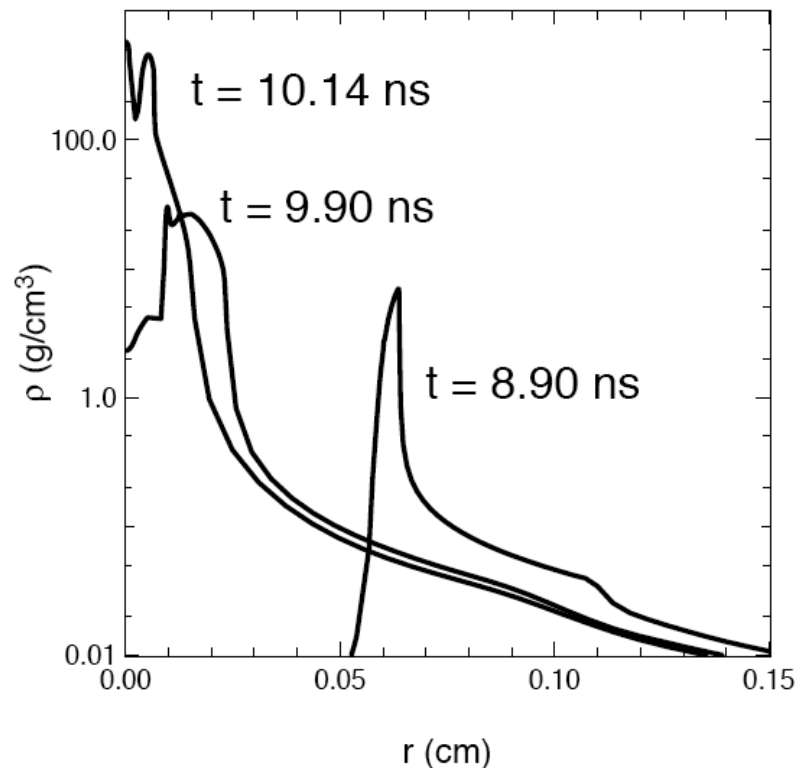


The large stand-off distance between the critical density, where light is absorbed, and the fuel may lead to low η_{ign}

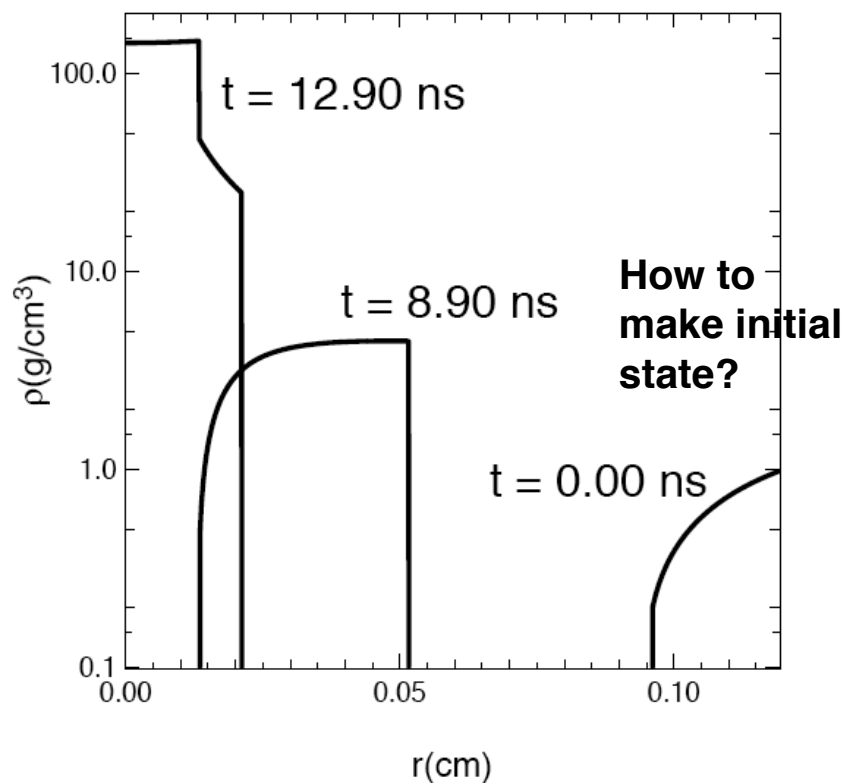


Novel implosion designs can eliminate the low density central region of conventional implosions

**Hi-Z in core produces
radiative collapse
10% energy cost**



**Self-similar implosion takes
a shell of fuel into a uniform
sphere**



**This isochoric assembly can also provide a
platform for EOS and opacity experiments**



Most research has concentrated on optimizing η_{ign}

- **Generation of fast-particles**
- **Laser propagation**
- **Transport of energy from critical surface to fuel**

High intensity light can couple efficiently to dense matter via collisionless mechanisms



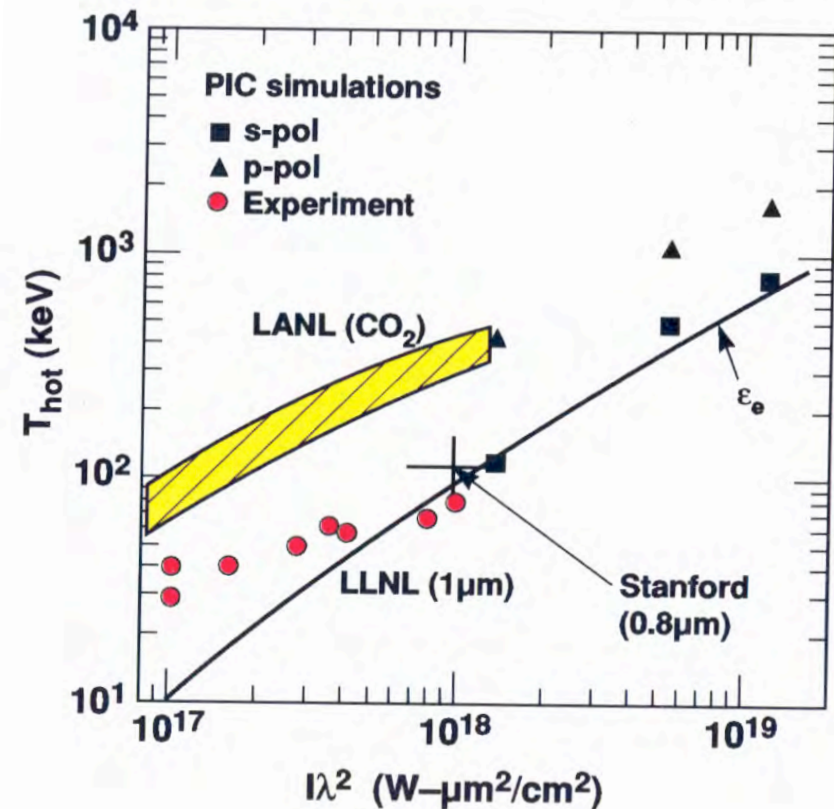
Two mechanisms:

If E points into plasma,
oscillatory excursion $>$ plasma scale height
Electron doesn't feel decelerating field
'Not-so-resonant resonant absorption''

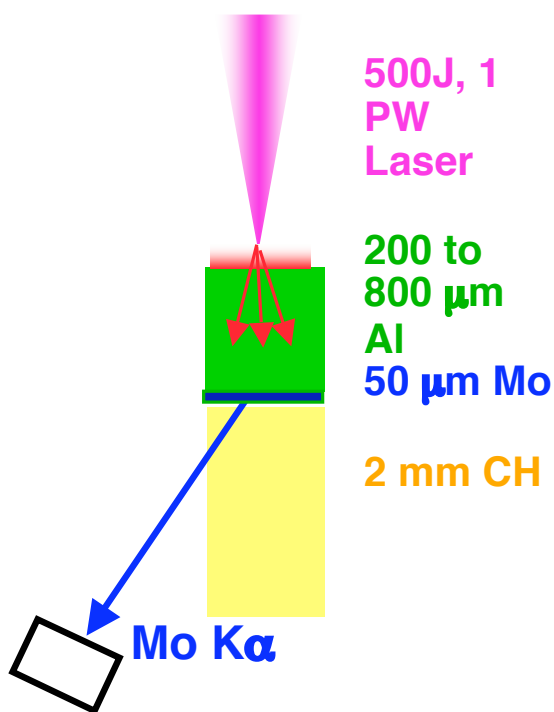
If large E parallel to plasma
 B field will rotate motion into plasma
Electron in vacuum would have figure 8
Absorption increases with intensity
"J x B heating"

Rippling of surface increases absorption

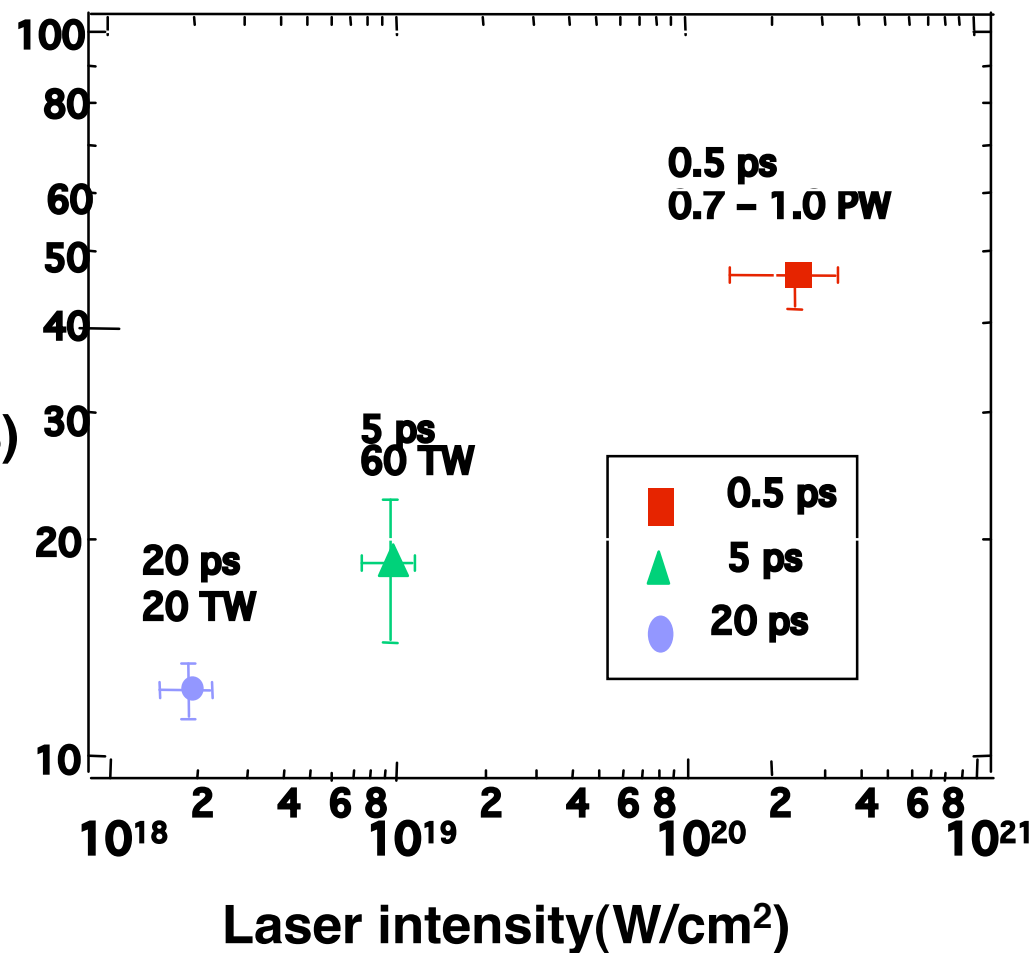
PIC simulations see absorption 40–50%
Sometimes 90% with holeboring at high I



The short-pulse laser coupling to electrons going forward into solid slabs is high

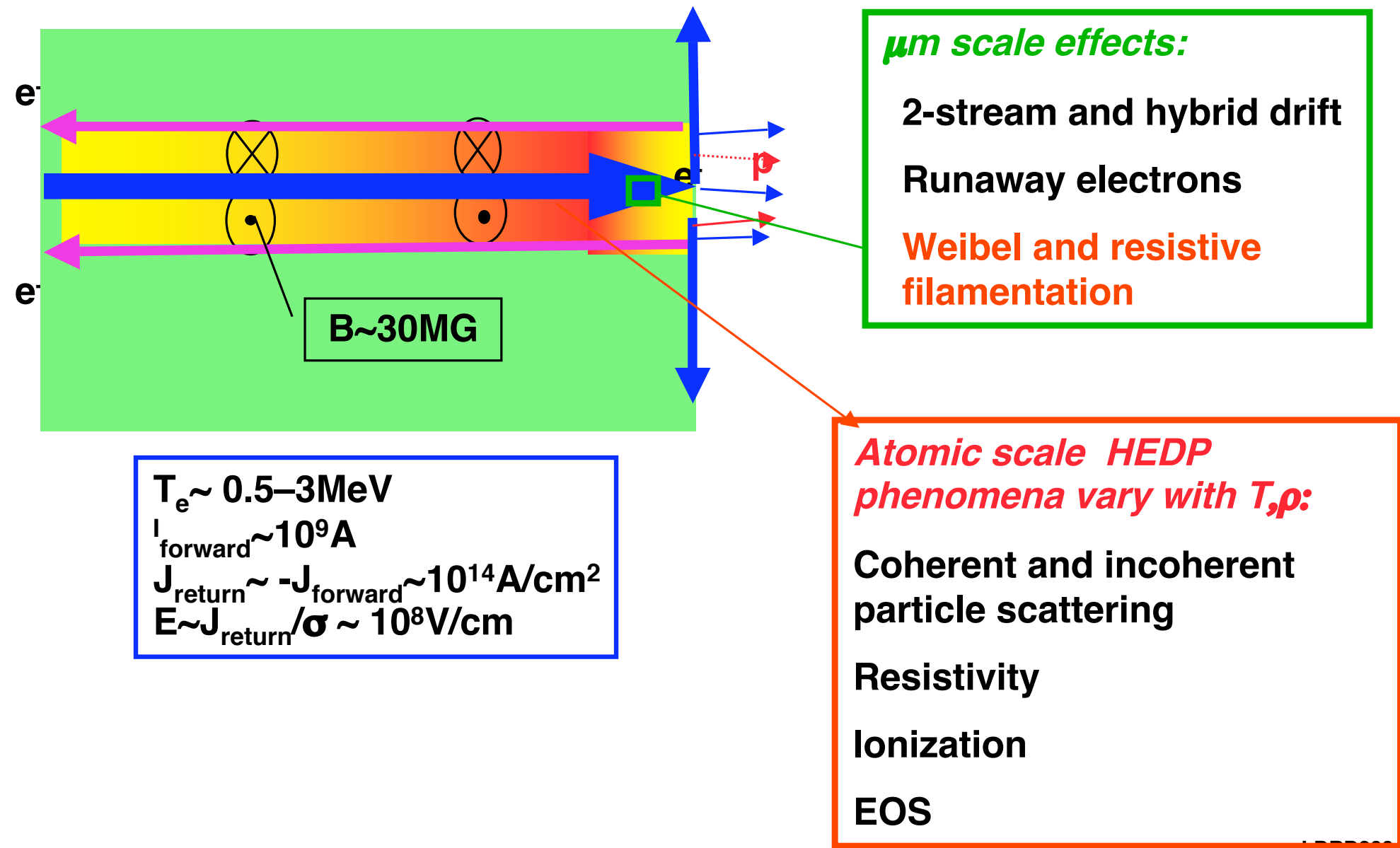


Conversion*
efficiency(%)



Coupling may actually be higher—analysis does not yet include self-consistent E,B fields

Electron transport from the critical surface to the ignition region depends on physics at multiple scales



The transport of electrons is controlled by multiple scattering, effects of macroscopic E&B fields and possibly by microinstabilities



Scattering affects range and angular distribution

$$dE/dx \sim Z_{\text{eff}}^2 n_e / \beta^2 * \text{Log } \Lambda \Rightarrow \text{for relativistic } e^- \quad \rho(\delta x) \sim E$$

Deutsch has suggested $Z_{\text{eff}} \rightarrow 1$

Hots are so dense and fast that multiple electrons can scatter before shielding electrons move

$$\langle \theta^2 \rangle \sim Z_{\text{eff}}^2 \rho(\delta x) / L_{\text{rad}} p^2$$

Charges and currents produced by the laser are so large that nothing can move without significant neutralization

$$\text{Power} = I V \quad \text{or } 10^{15} \text{W} = 1 \text{ MV} * 10^9 \text{A} \quad (\text{Alfven current} \sim 5 * 10^4 \text{A})$$

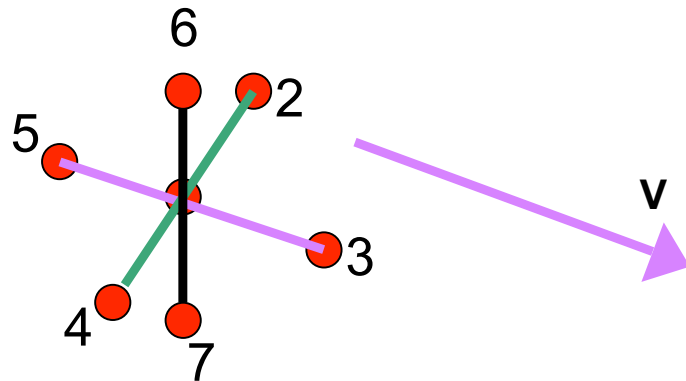
$$\text{Curl } B = j * \mu_0 \Rightarrow B = I \mu_0 / (2\pi r) \quad \text{or for } r=30 \text{microns} \quad B=6.7 * 10^{10} \text{ gauss}$$

$$\text{Energy} = QV \quad \text{or } 10^5 \text{J} = 1 \text{ MV} * 0.1 \text{ Coulombs}$$

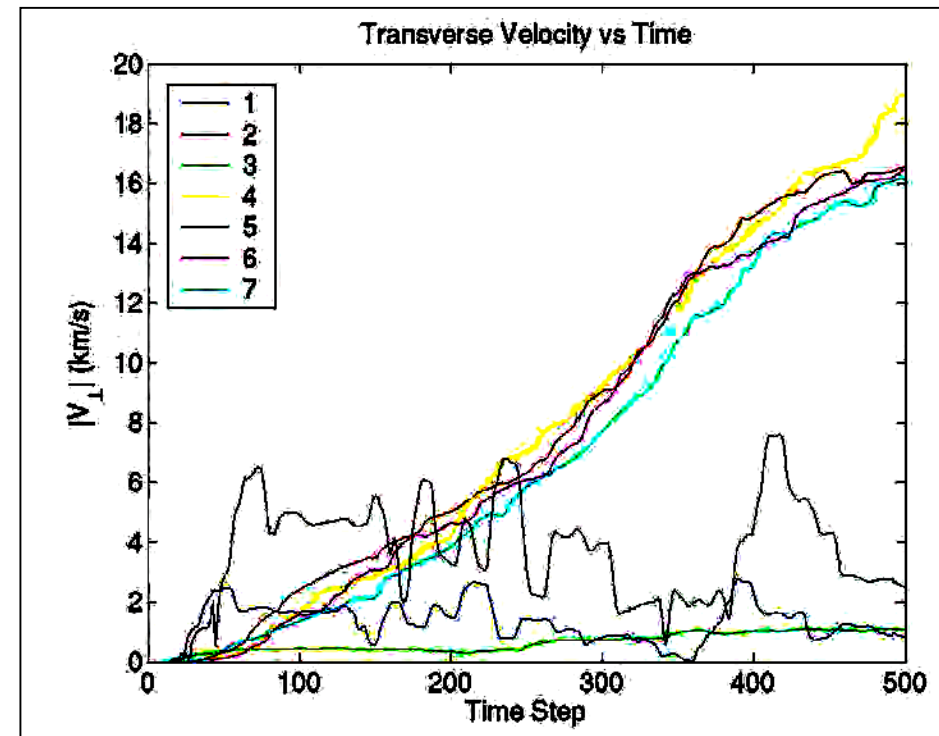
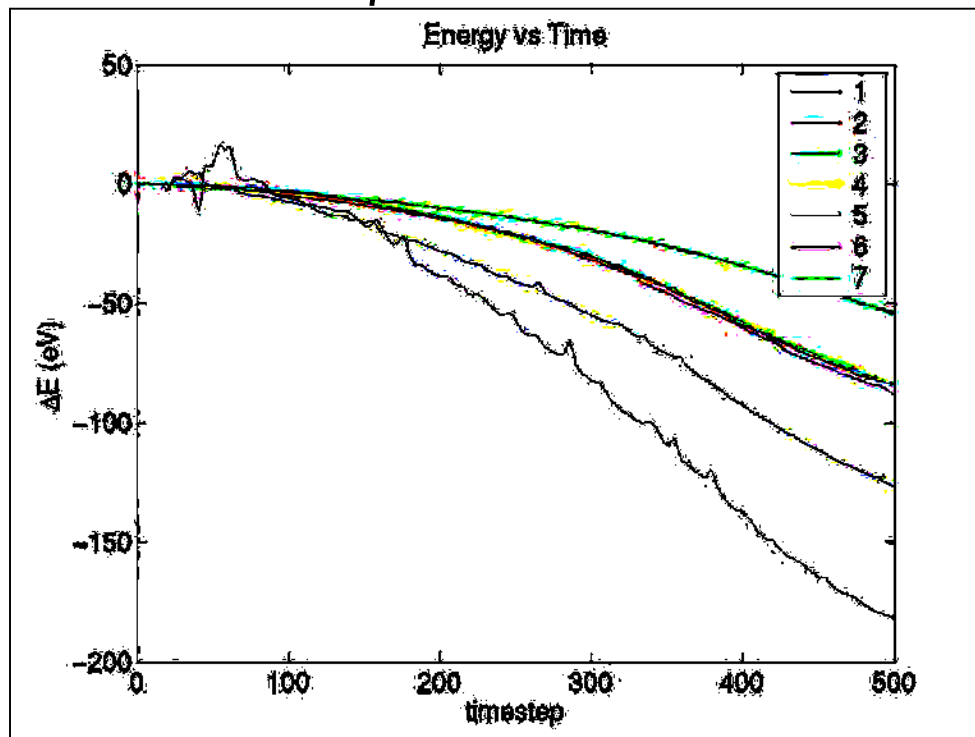
$$\text{Div } E = \rho / \epsilon_0 \Rightarrow E = Q / (\epsilon_0 2\pi r^2) \quad \text{or for } r=30 \text{microns} \quad E=9 * 10^{16} \text{ V/m}$$

In some simulations microinstabilities(filamentation, 2 stream) show stopping Power $\sim 10^4$ classical, possibly not seen in normal density experiments

LSP was used to study a constellation of electrons propagating through FI plasma



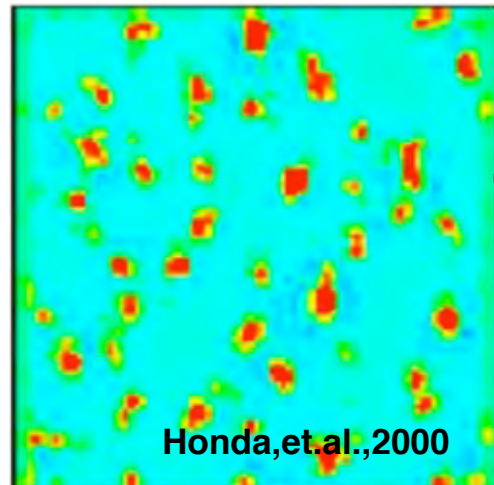
1 MeV e^- with spacing 10^{-8}cm
into plasma with $n_e=10^{26}/\text{cm}^3$
Stopping $\sim 6\times$ single particle rate!



Modeling shows that collisionless filamentation of cold electron beams can lead to anomalous stopping

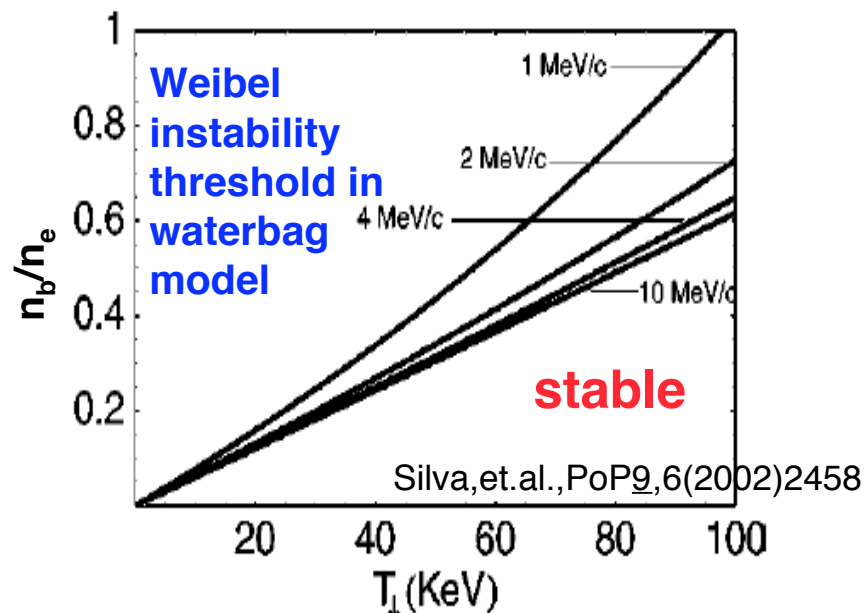
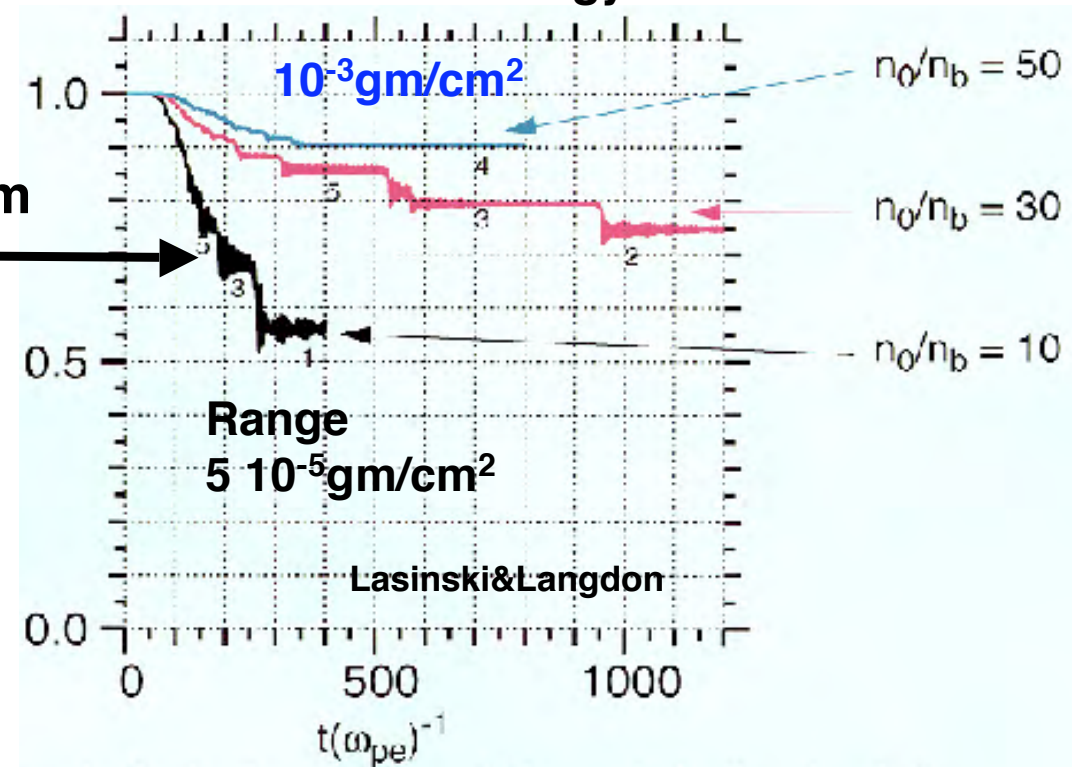


Electron filaments
in 2D PIC



Cold beam

Beam energy



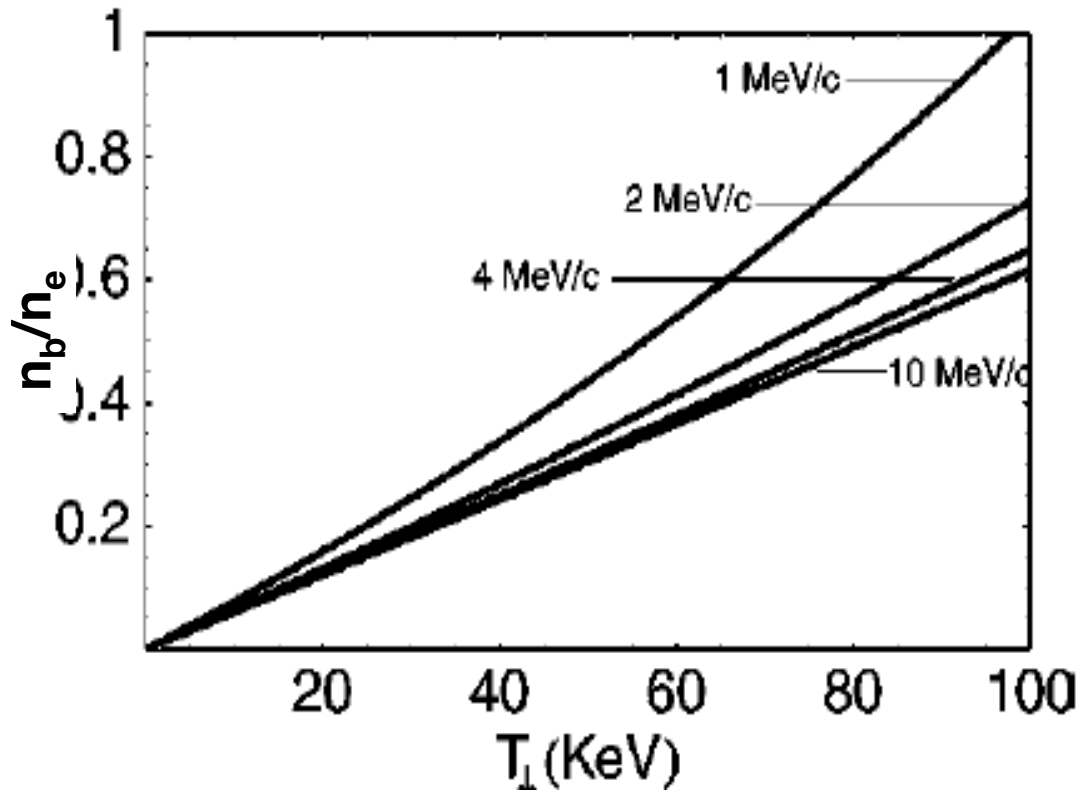
• Filamentation is reduced by beam temperature and density ratio

• Collisional calculations don't have hard T_{\perp} cutoff

Analytic models show that microinstabilities are suppressed by beam temperature and large n_e/n_b (but by different amounts)



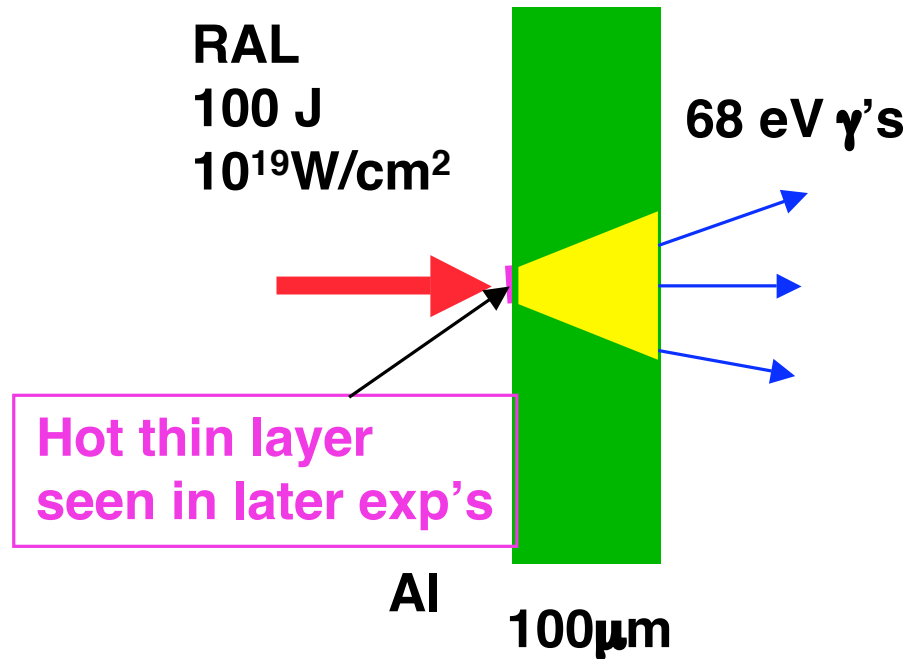
Weibel instability threshold



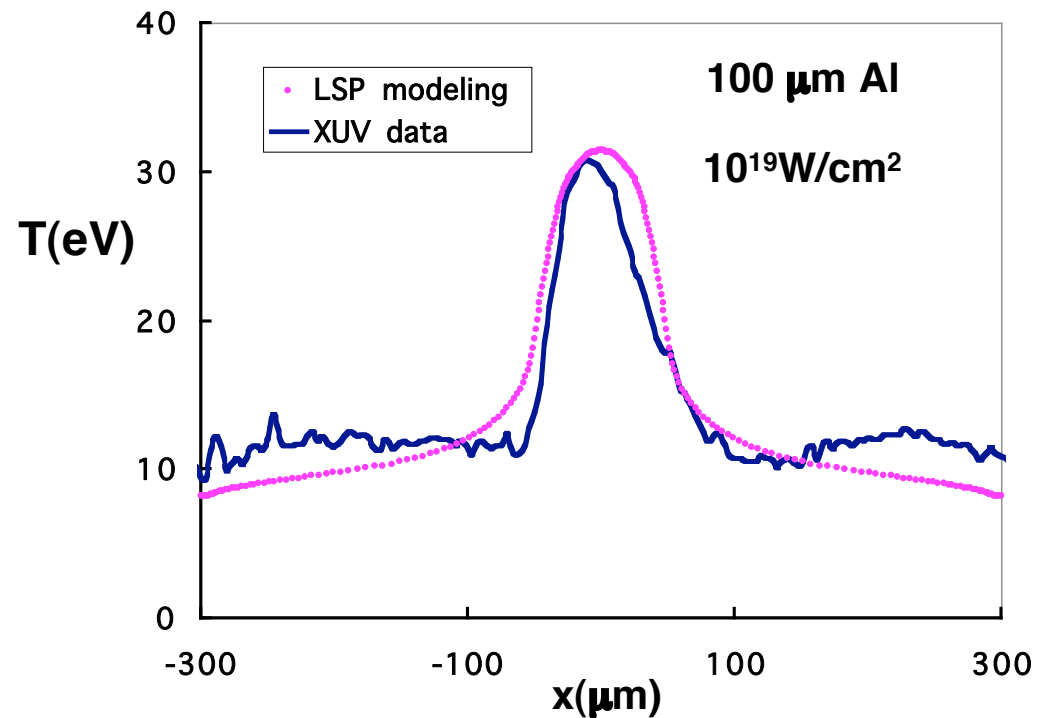
Uses waterbag distribution:
Fixed longitudinal momentum
with tophat transverse
distribution

Silva, et.al.

Most electron energy propagates without extreme anomalous stopping, but some mysteries remain



Entry e⁻ spot ~5X laser spot
~20° cone half angle



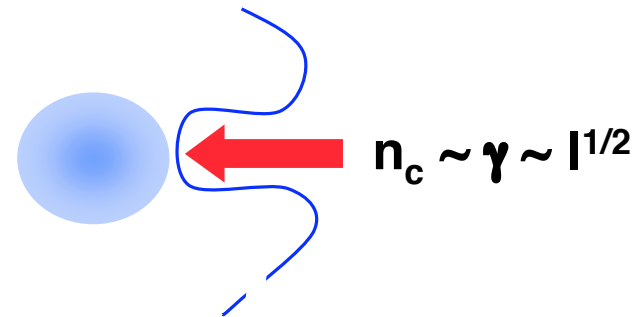
- Phenomenological coupling using given laser distribution
- $T_{\text{perp}} = 300 \text{ keV}$
- Beam spot at 100 μm
standoff is marginal for direct heating

We can shorten the distance between the critical density and the ignition region

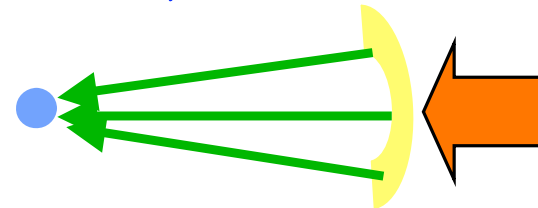


Challenge: deliver energy to 40 μ diameter spot from 1–3 mm away

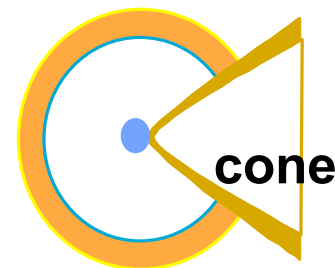
Hole boring and relativistic transparency



Protons can be ballistically focused of long distances



Cone focus geometries do not produce coronal plasma in the short pulse laser path



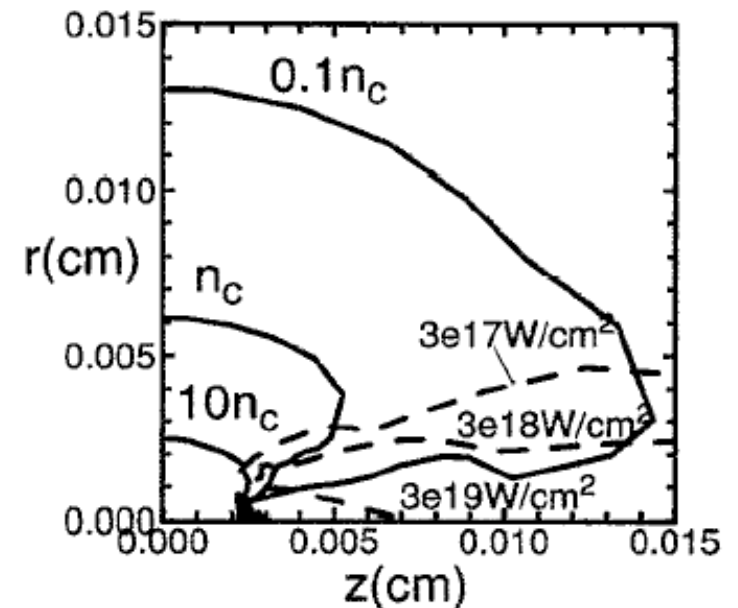
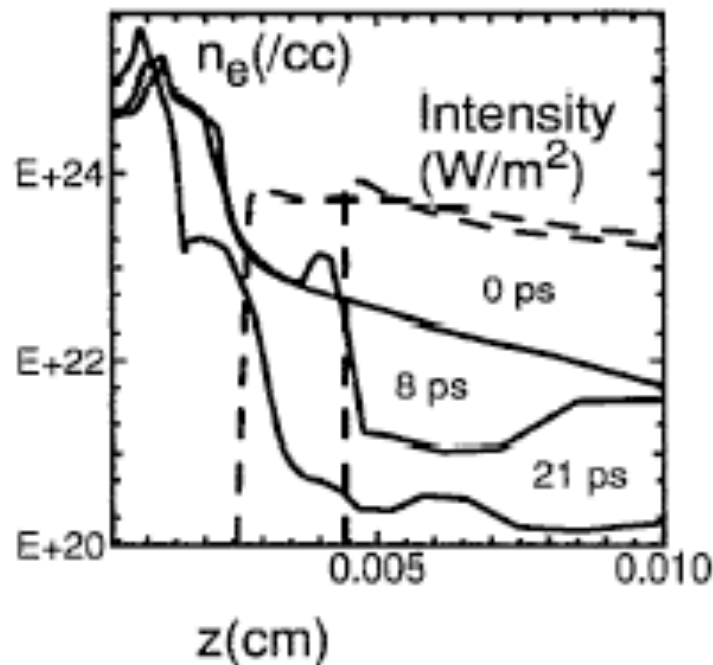
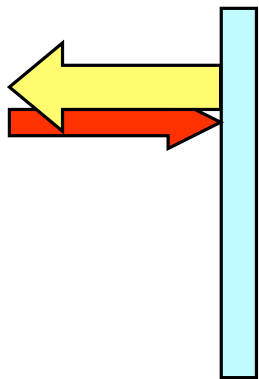
Several schemes to shorten distance between critical density and the ignition region were explored



The compressed fuel is produced by an implosion
The critical surface has radius \sim initial radius \sim mm
How can we hit $30\mu\text{m}$ spot from this distance?

Ponderomotive holeboring, relativistic transparency and/or cone focus geometry are possible routes to reduce this distance

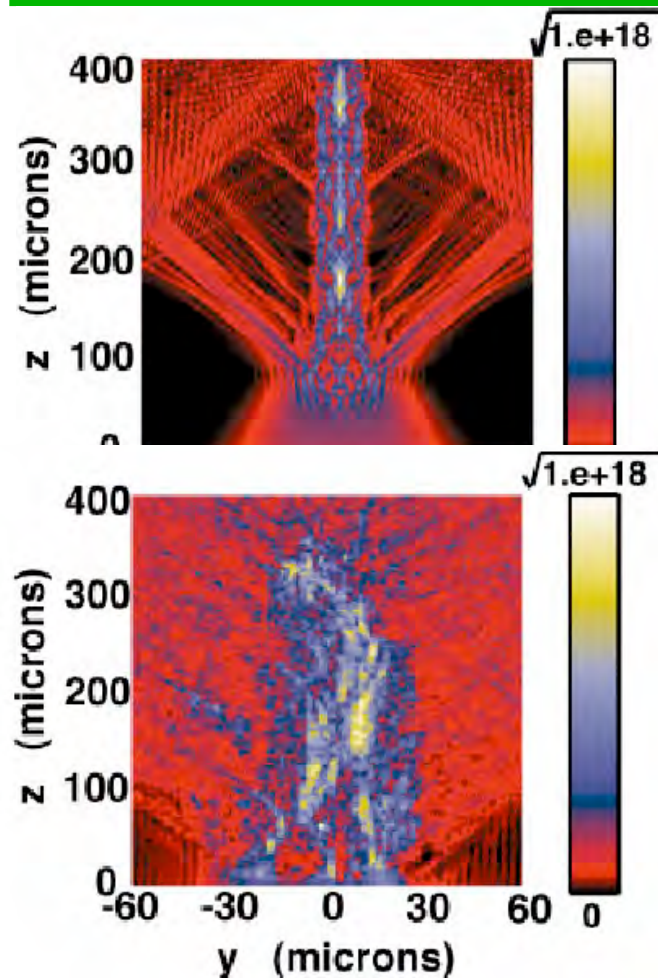
$P=2I/c$ for mirror



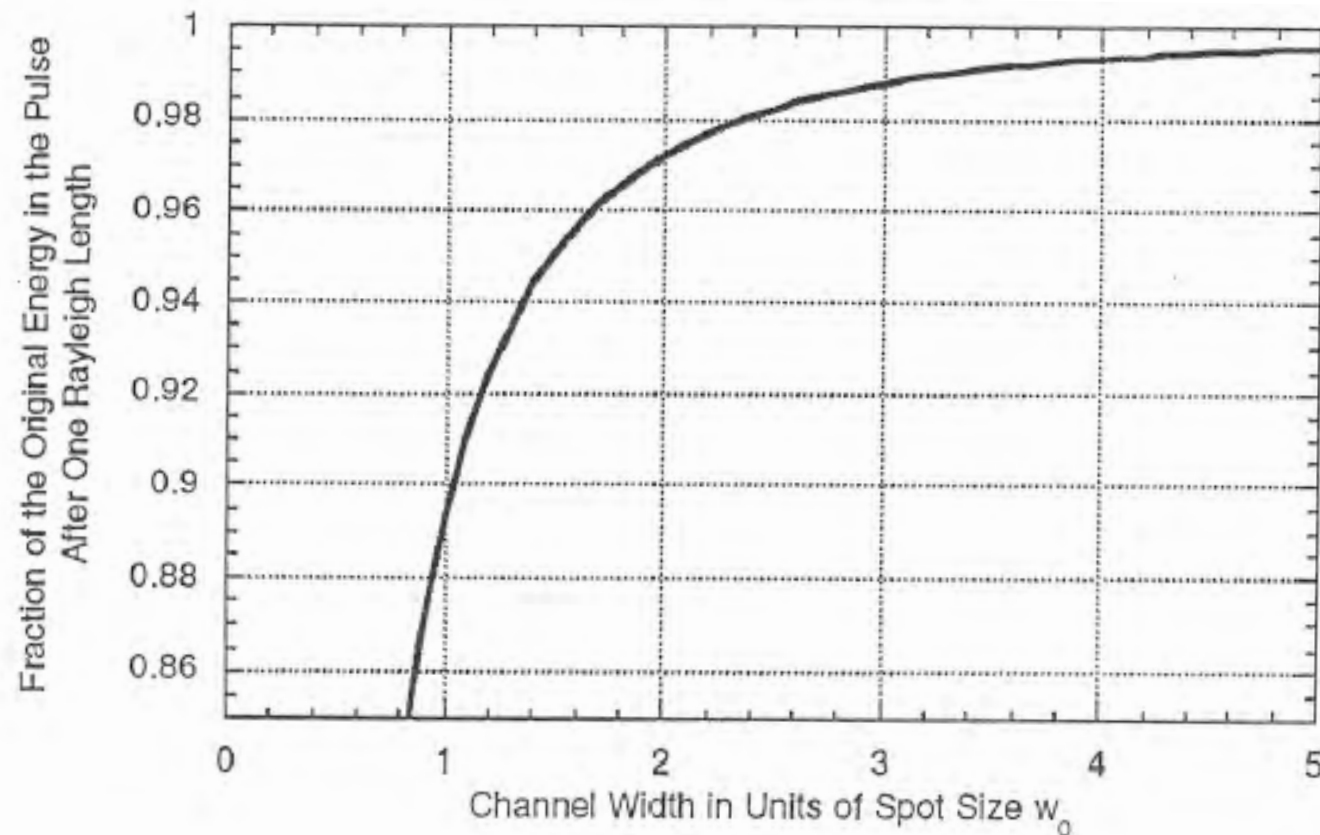
As the sole technique to reduce the distance between critical and high density, hole boring is probably insufficient



Aberrated beams likely to filament

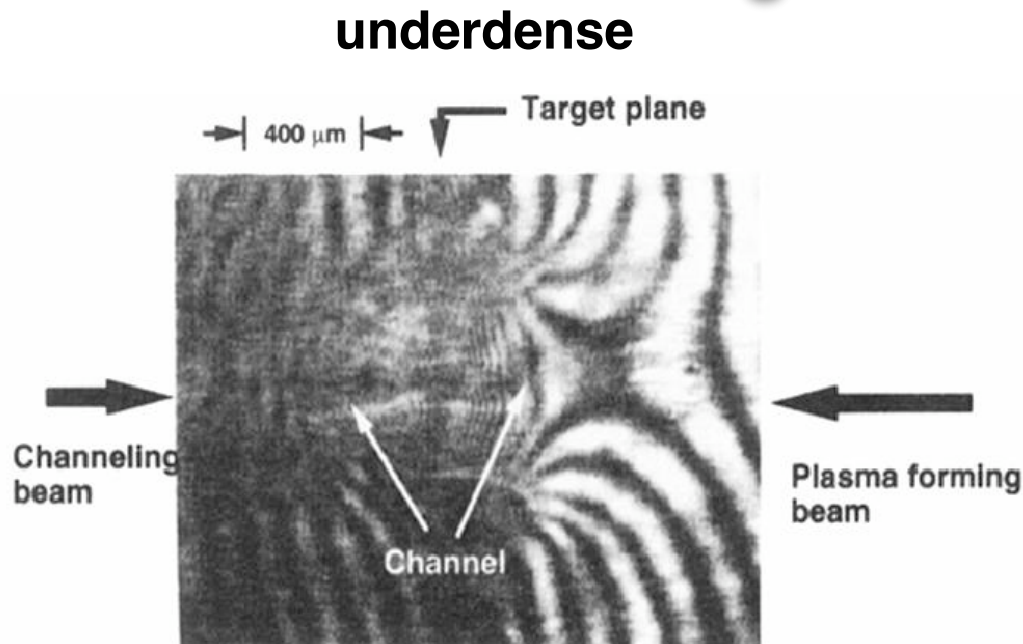


Large channel aspect ratio will lead to significant losses on walls

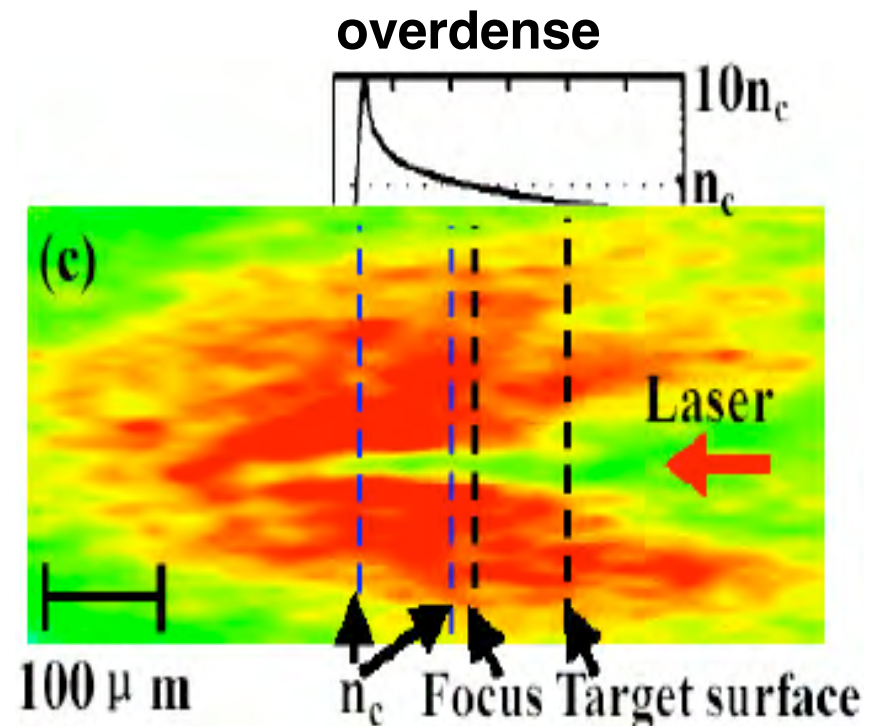


No experiment has demonstrated propagation through mm's of plasma with good efficiency. Still possible for smaller plasmas.

Experiments have demonstrated channel formation and energy transport up density gradients



60 J in 500 ps*
propagates through
peak $n = 0.3n_c$ with 80%
efficiency

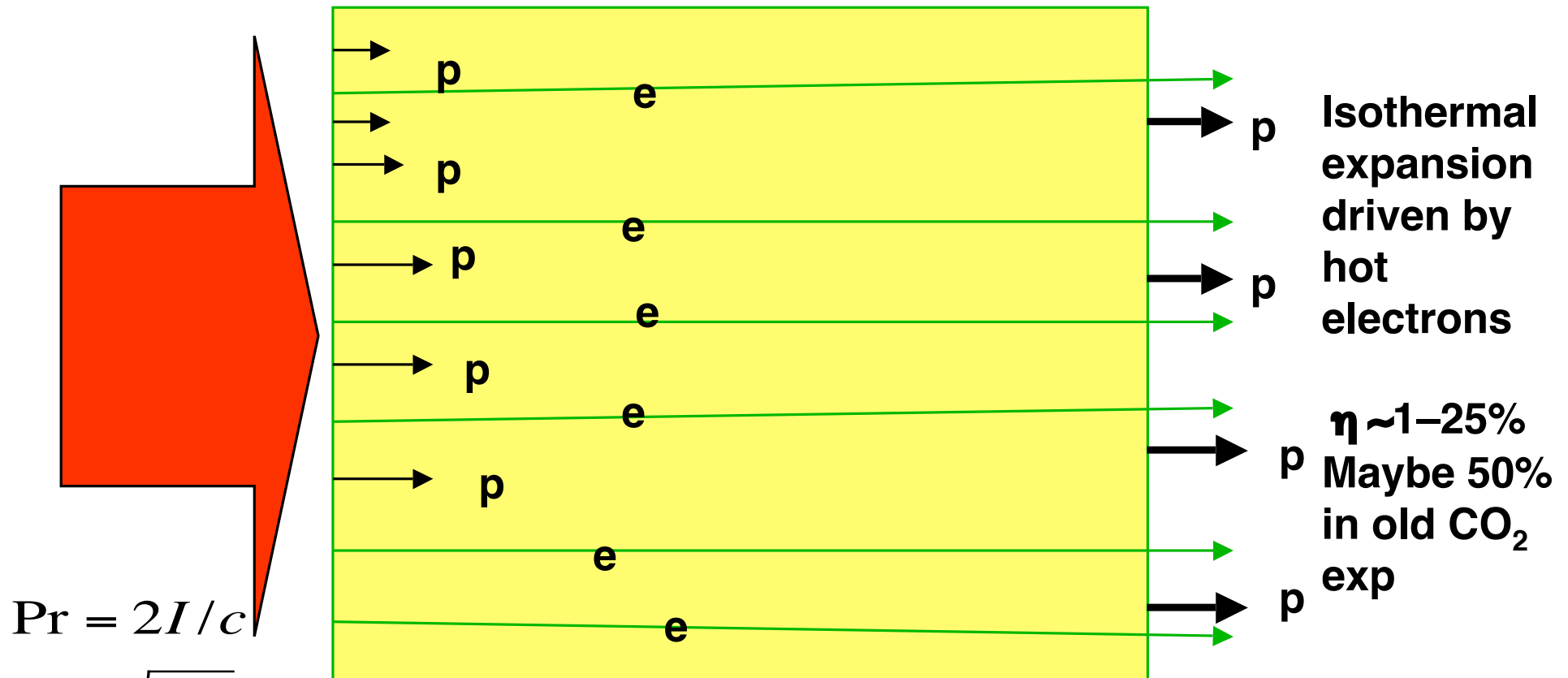


PW# laser relativistically self
focuses and propagates several
hundred μm through overdense
plasma with $\eta = 5\%$

But, coronal plasmas are have mm extent
Holeboring pulse took 100's of ps even for 500 μ plasma
Transmitted pulse may be filamented

* P.E.Young,et.al, PRL75,6(1995)1082

Protons can be accelerated directly with ponderomotive pressure or via a virtual cathode at the rear surface



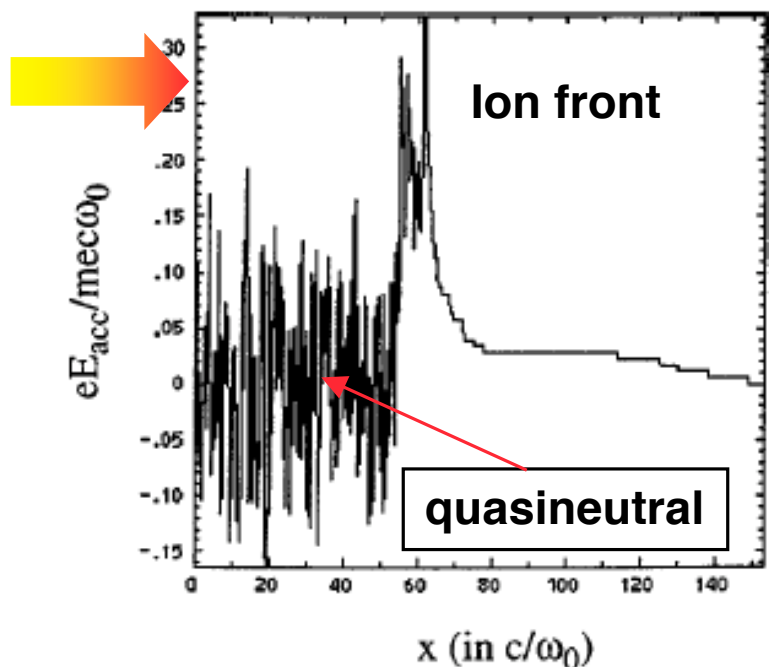
$$Pr = 2I/c$$

$$u = \sqrt{\frac{Pr}{2\rho}}$$

$$\eta = \frac{uPr}{I} < 3\% @ 10^{19} \text{W/cm}^2$$

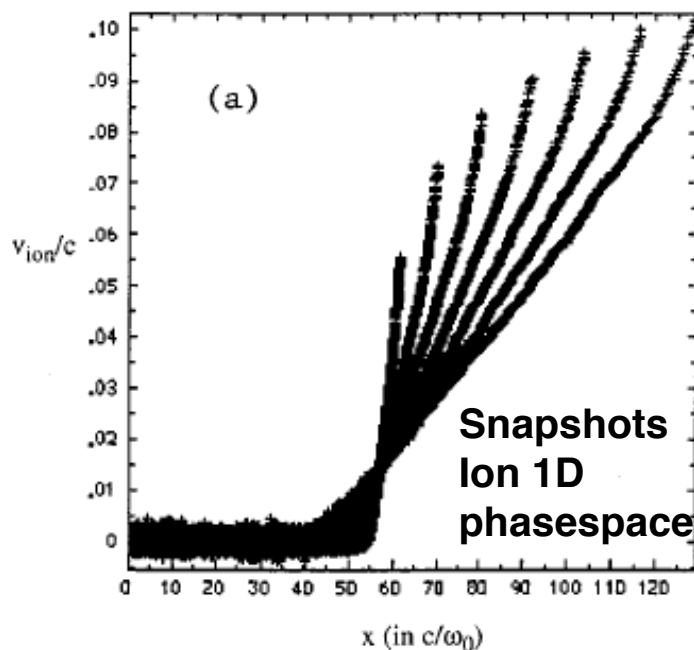
Amazingly bright source

Laser-produced electrons can accelerate ions to high energy

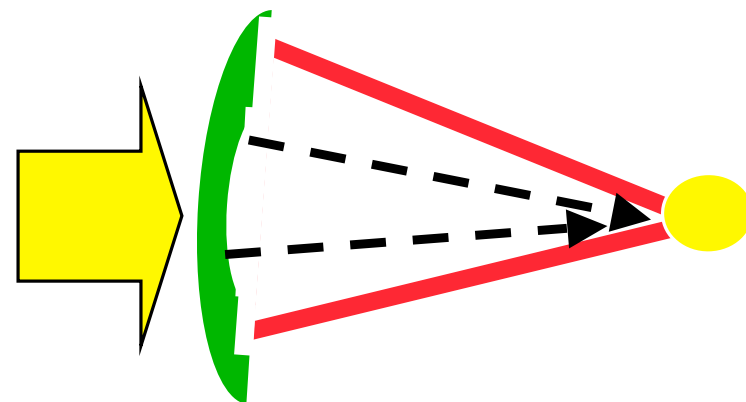


**Fast electrons leaving slab*
set up sheath fields**

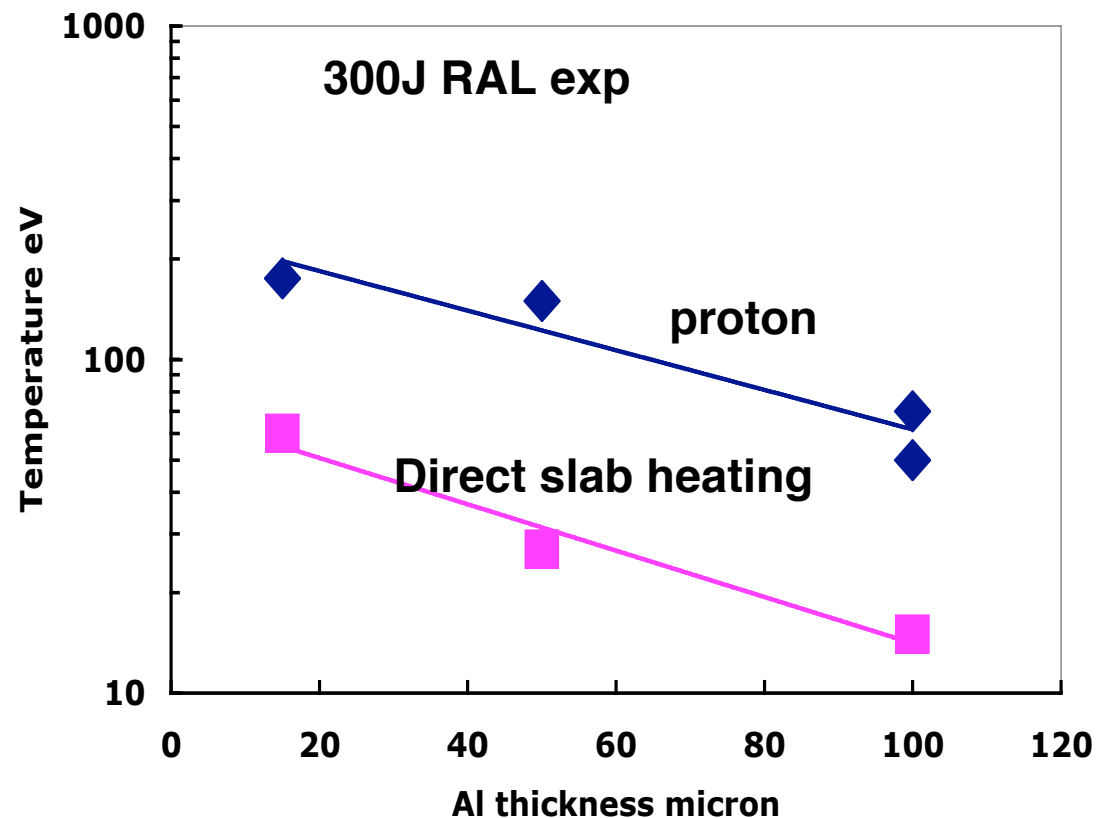
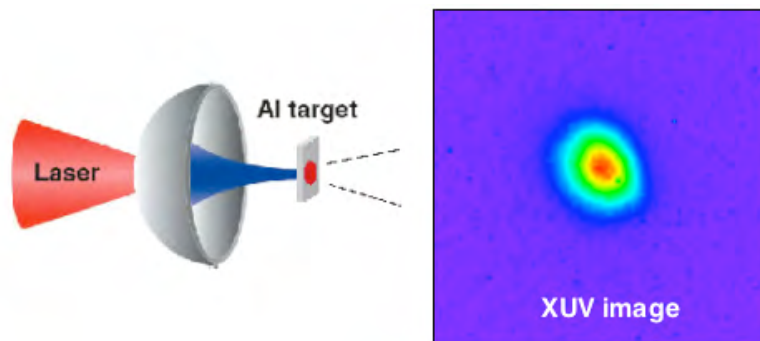
- Sheath is thin \Rightarrow foil shape determines focusing
- Ballistic focusing \Rightarrow standoff ignition of fusion fuel



Fields accelerate ions



Proton beams have heated matter to 100's of eV* but issues remain for FI applications



Issues:

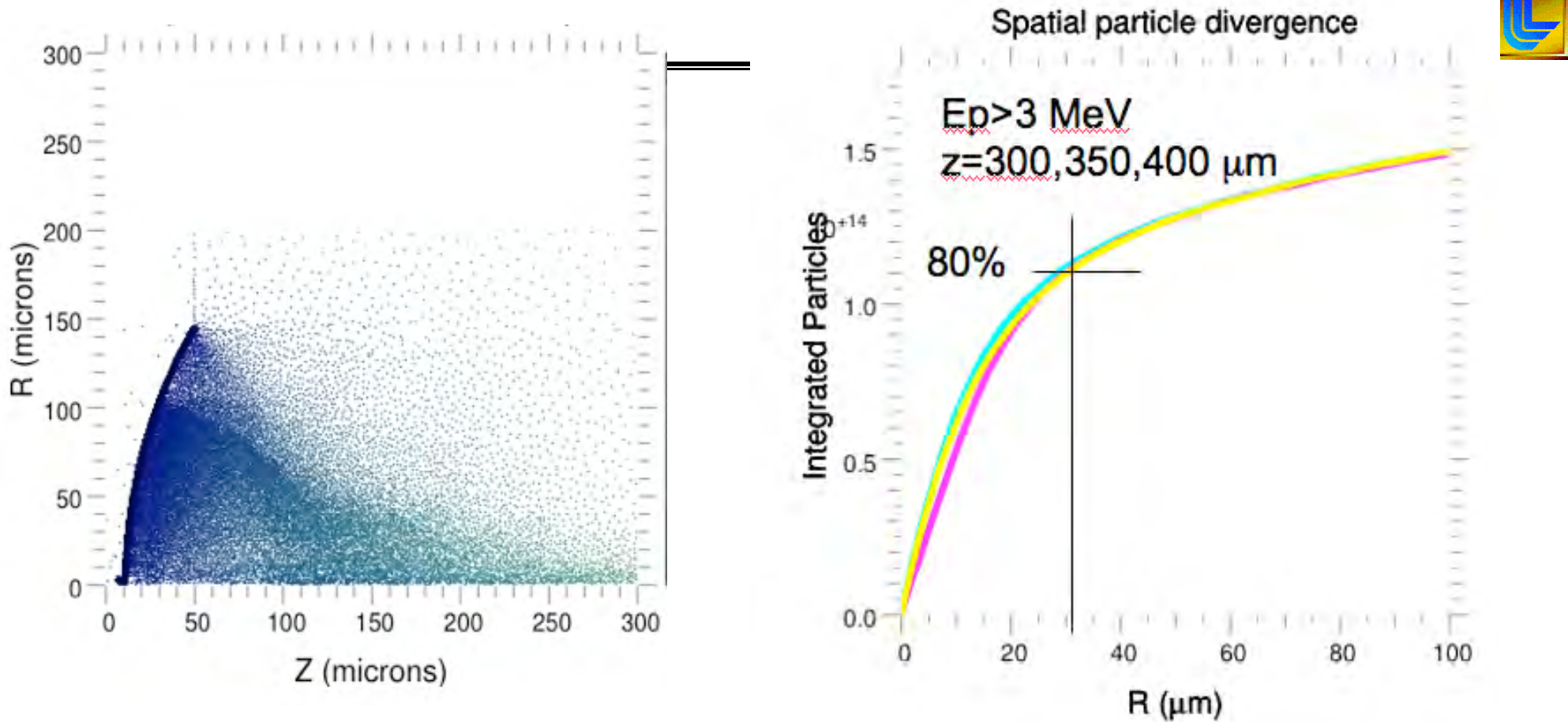
Efficiency

Scaling to large energies and long pulses

Multiple scattering

Beam-plasma instabilities

Modeling of focusing suggests that 80% of energy at $>3\text{MeV}$ can be delivered to $60\text{ }\mu\text{m}$ focal spot from an f/1 segment of a $300\text{ }\mu\text{m}$ radius spherical shell

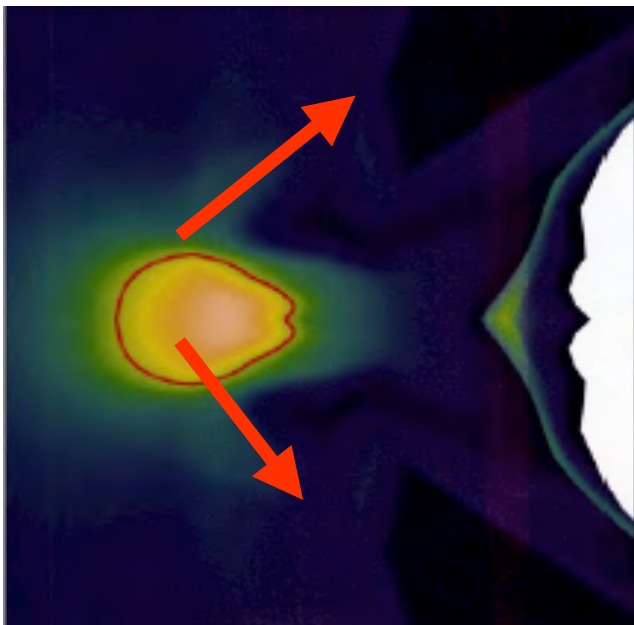
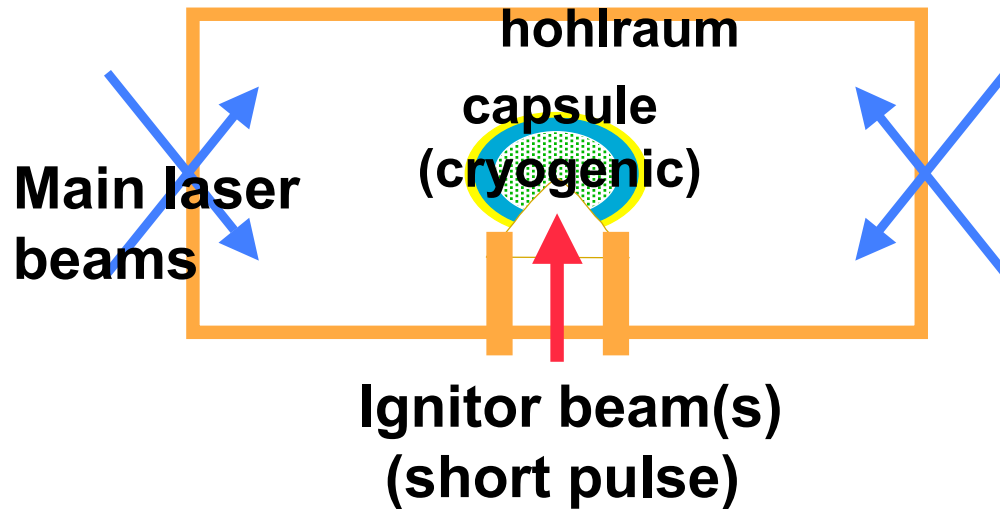


**10 μm Au, 1 μm H , T_{hot} 3 MeV , 47% conversion to protons $>3\text{MeV}$
Hybrid PIC modeling by M Foord LLNL using LSP code**

Cone focus designs provide access to assembled core



A NIF-like scheme



Hydro issues:

- Entrainment of cone material
- Produce imploded core without central void and good efficiency

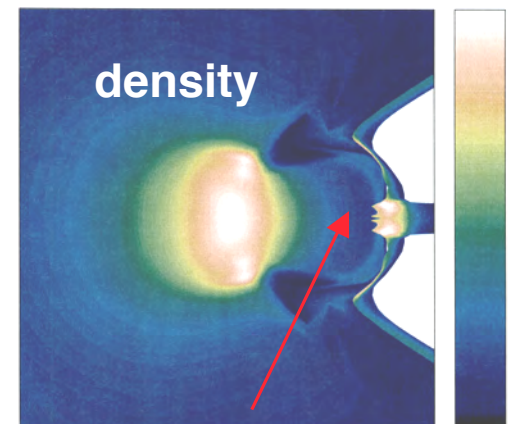
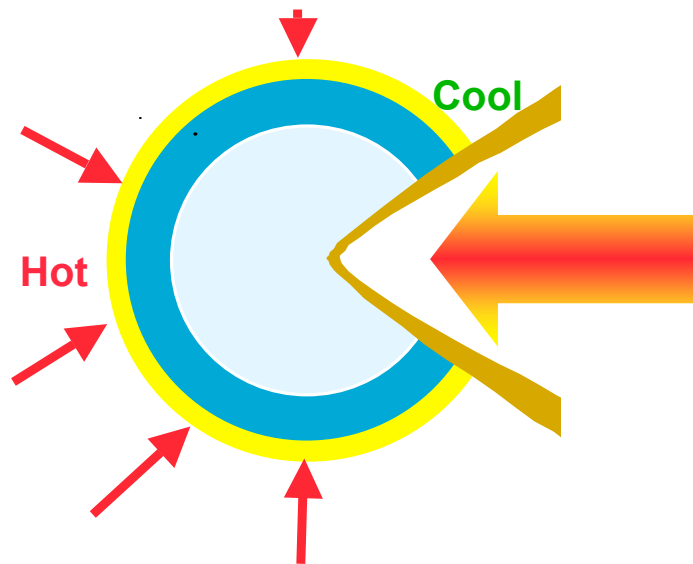
Light coupling issues

- Collect and focus light from large area
- How does light scatter from cone?
- How will light scatter in prepulse plasma?
- What is nature of hot electrons produced?

Cone focus geometry provides an open path for the ignition laser and permits fuel assembly



Capsules with reentrant cones assemble fuel into compact masses



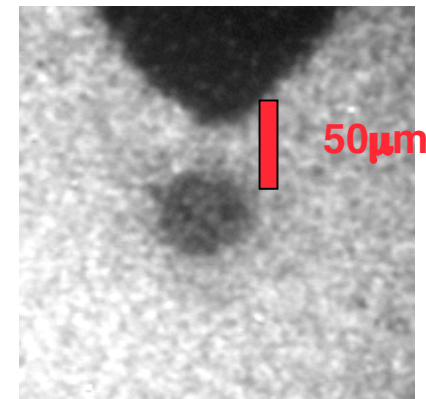
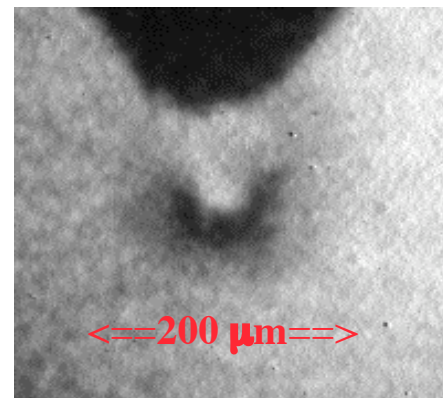
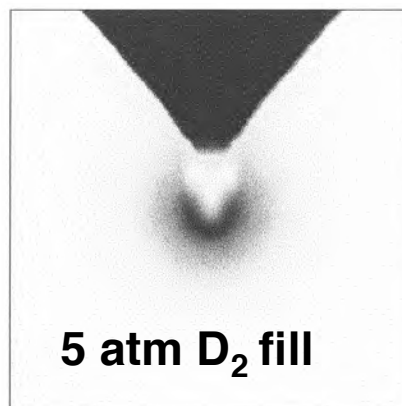
Low density core is ejected

Lasnex

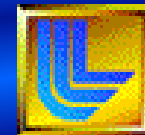
Backlit experiment

+Fe filter

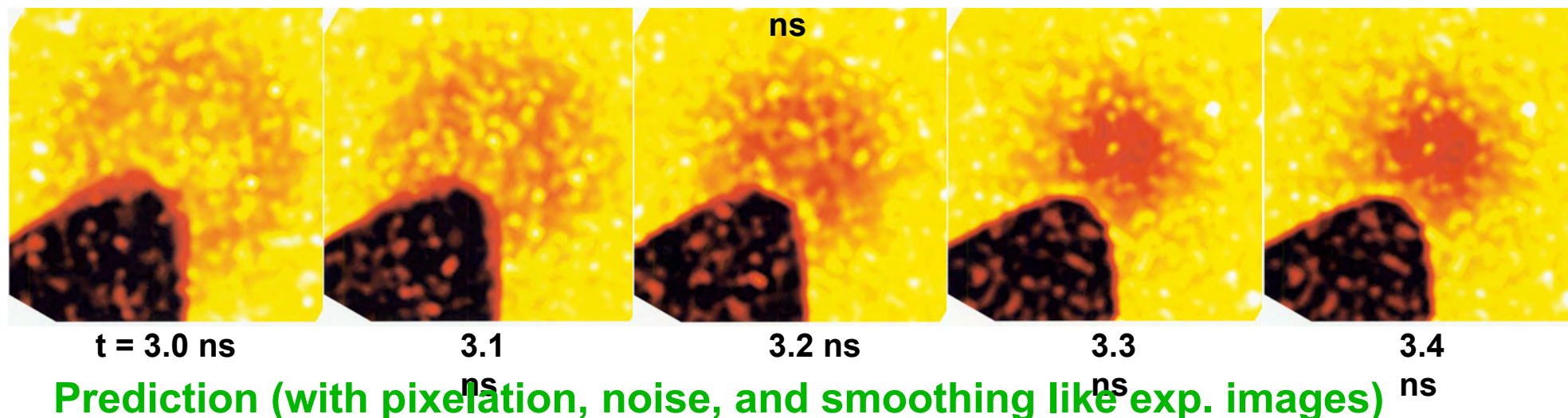
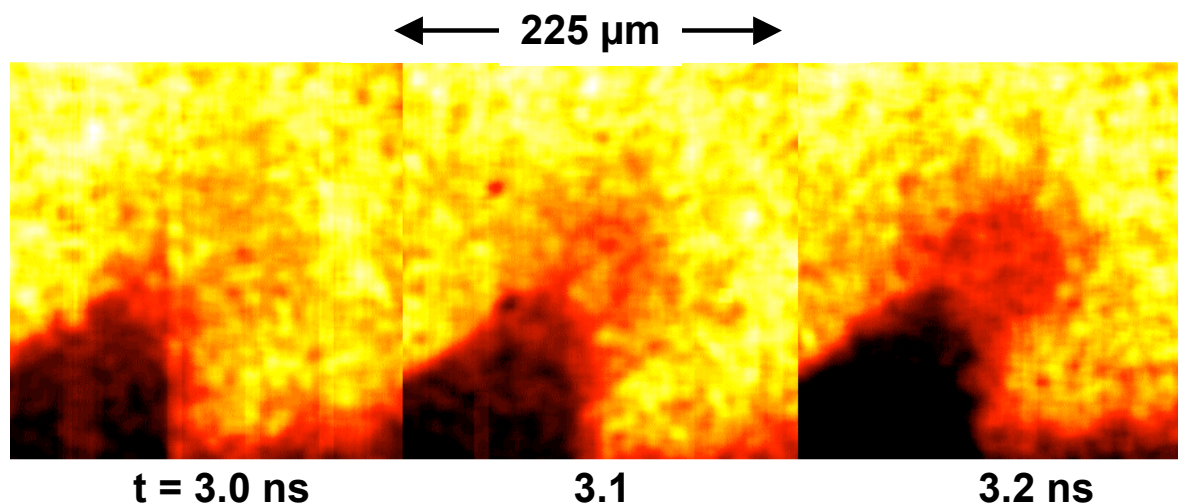
Lasnex simulations* accurately describe experiments at the Omega laser



Backlit images (@8 keV) show convergence of cone-focussed targets was very similar to prediction — with perhaps a small time offset.

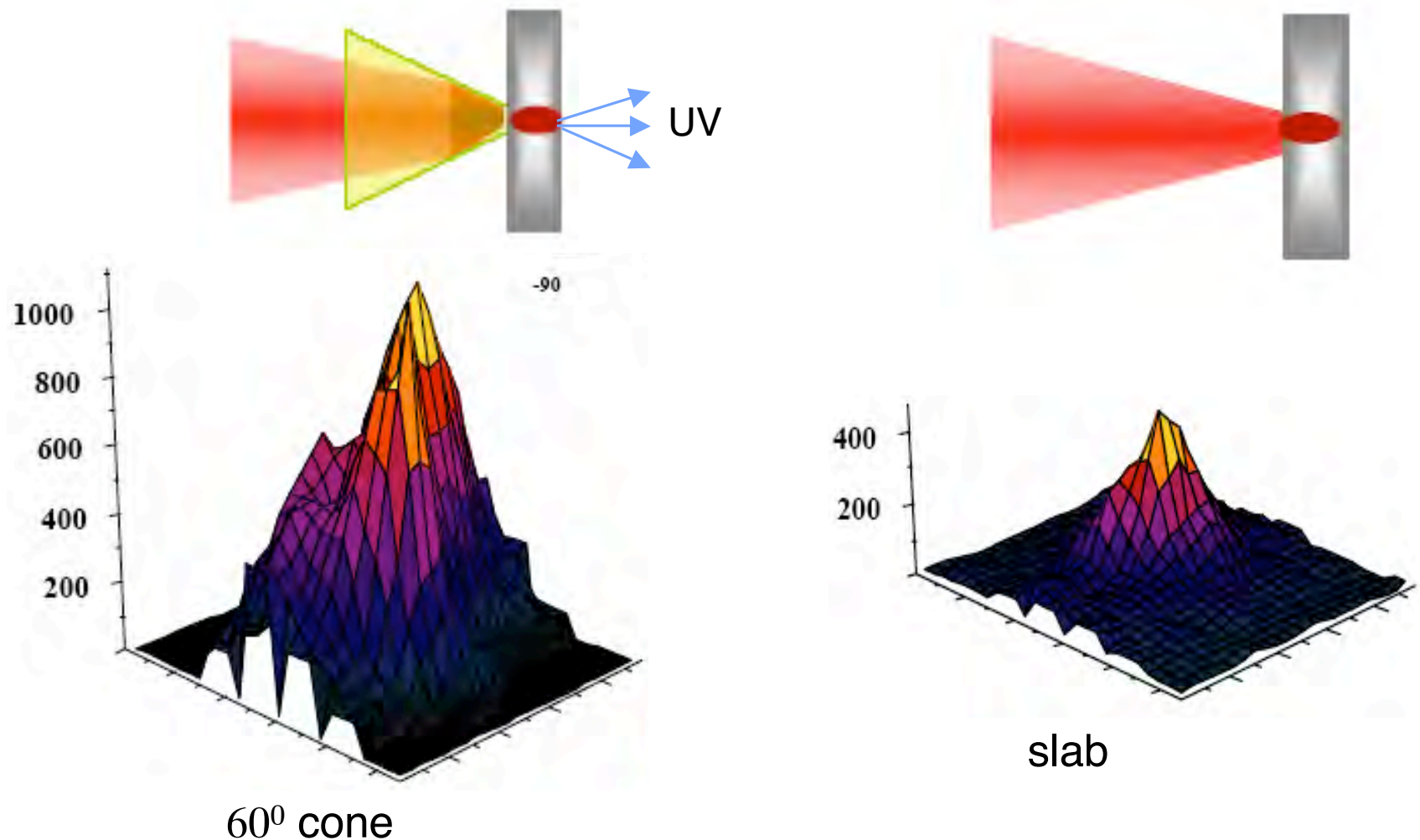


Experiment



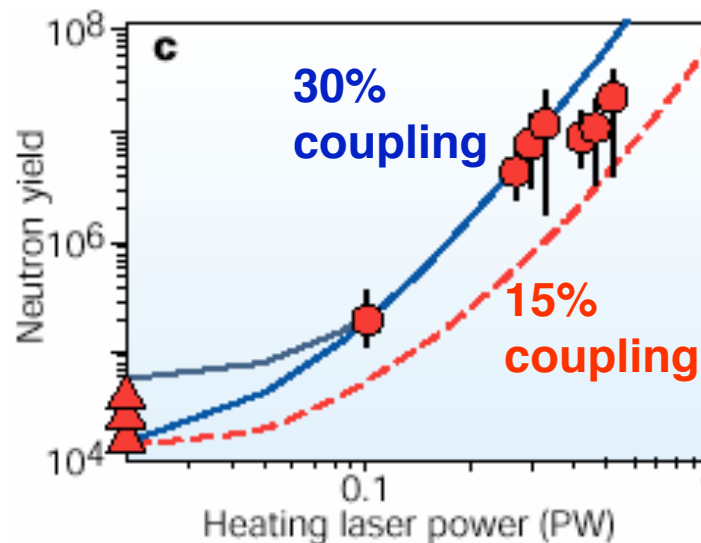
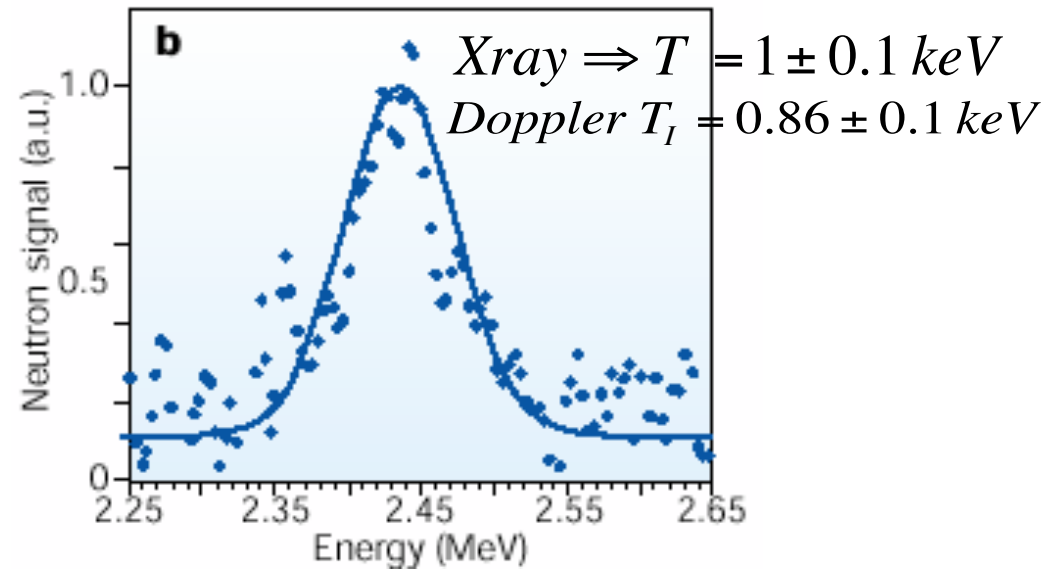
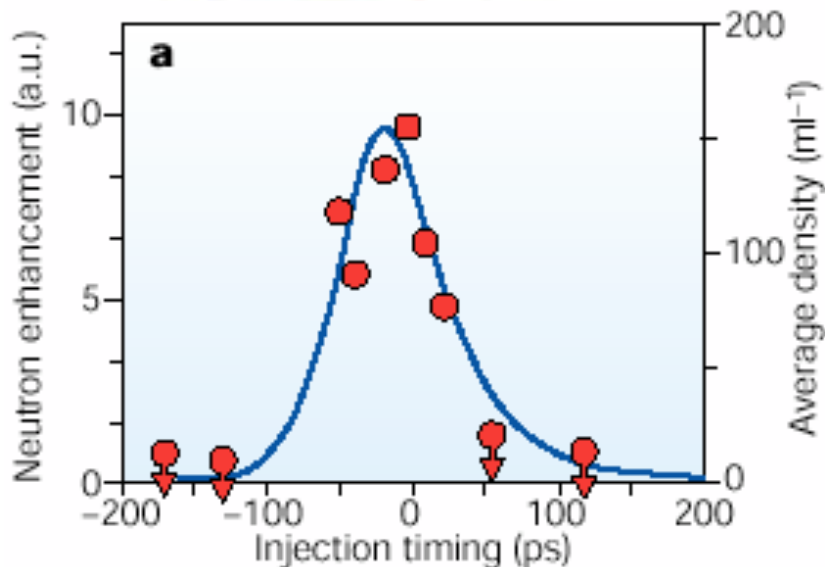
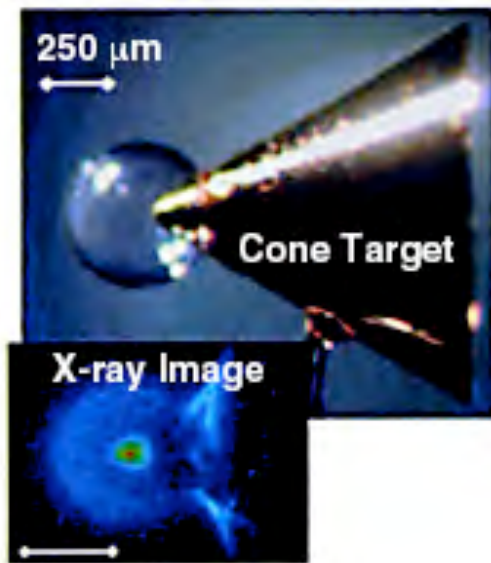
Comparison shows some exp. evidence for gold entrainment near tip of cone.

Experiments at ILE,Osaka* show 3X coupling enhancement in cones relative to slabs



Smaller angle cones may lead to order of magnitude intensity enhancement

Integrated fast ignition experiments from ILE, Osaka* show high (~25%) coupling efficiency

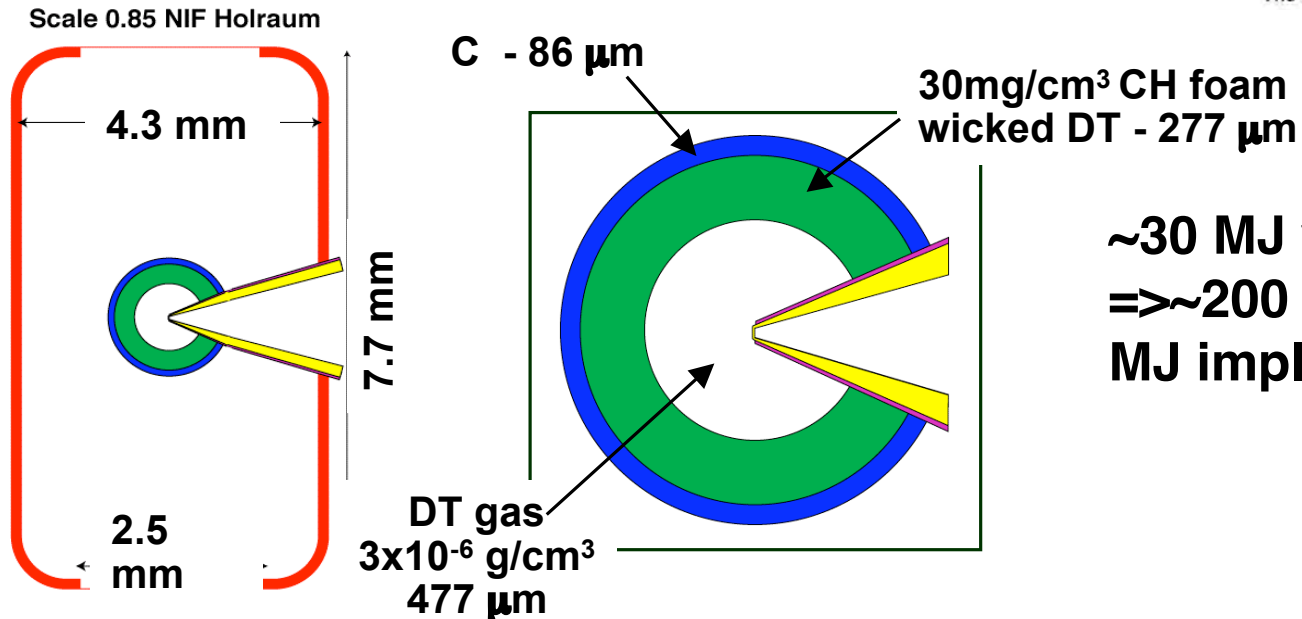


**1000 X
neutron
yield**

High gain Fast Ignition could eventually be achieved on NIF with ~ 0.5 MJ of long pulse energy and ~ 70 kJ of short pulse energy



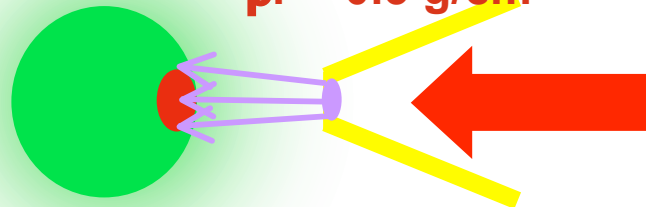
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~30 MJ yield
=> ~200 MJ with 1.2 MJ implosion

Fuel:
 $\rho \sim 300 \text{ g/cm}^3$
 $\rho r \sim 2 - 3 \text{ g/cm}^2$

Ignition spot:
~35 μm spot
 $\rho \sim 300 \text{ g/cm}^3$
 $\rho r \sim 0.5 \text{ g/cm}^2$

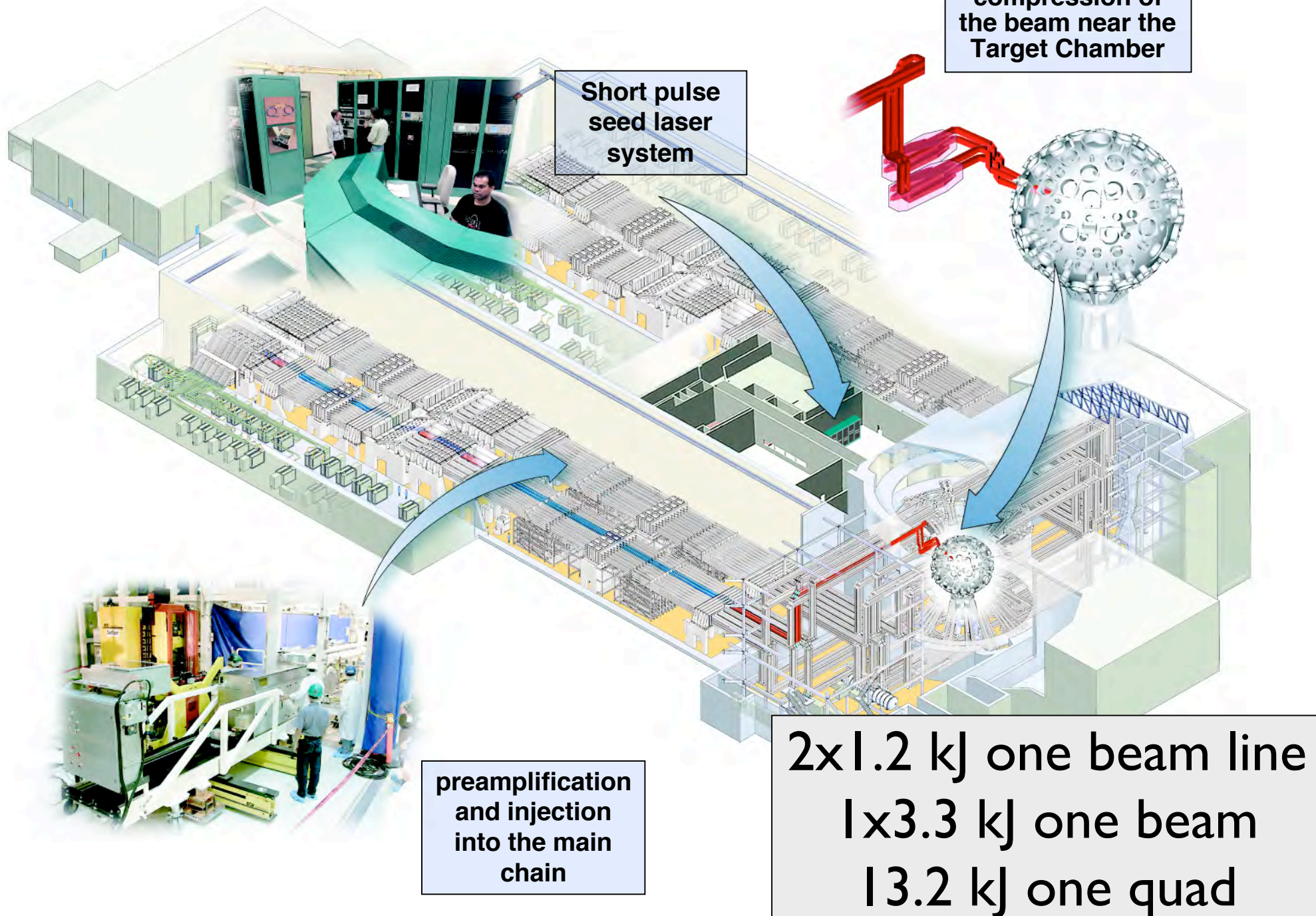


Short pulse laser:

$\eta_{\text{coupling}} E_{\text{laser}} \sim 18 \text{ kJ}$
=> $E_{\text{laser}} \sim 70 \text{ kJ}$

Determining η_{coupling} is the key issue

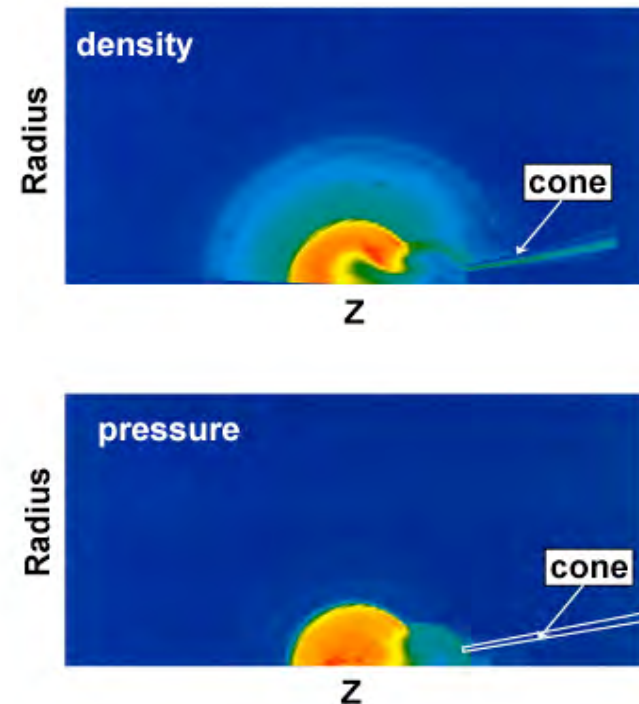
High Energy Petawatt Pulses on NIF



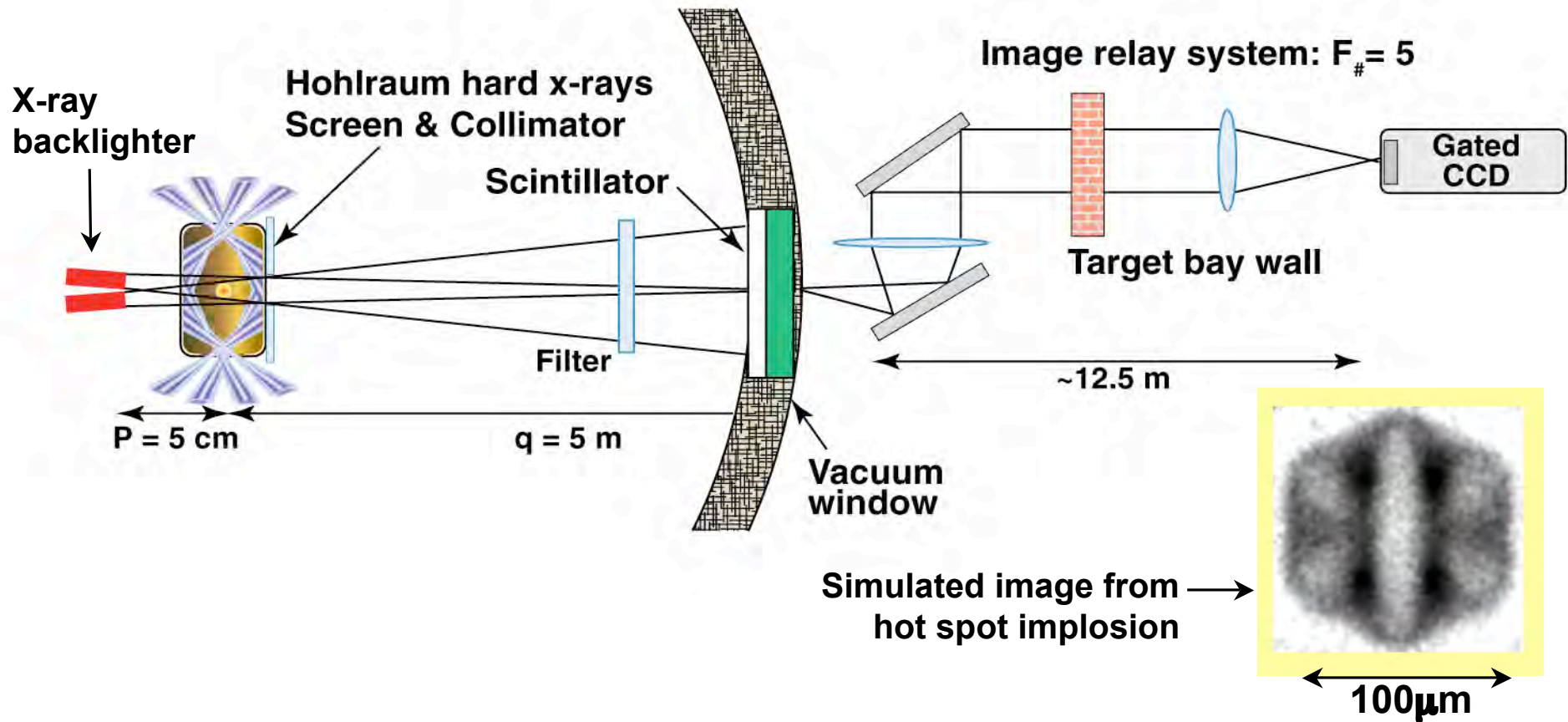
2D calculations show the compressed fuel is located about 50 μm from the cone tip

- The cone is made sufficiently thick to prevent shock breakout inside the cone
- With the fuel so close, no reasonable thickness cone tip can hold back the pressure at stagnation. Ignite before full shock reaches cone
- As a limiting case, this design had an open tip which led to blow-off into the cone region where the short-pulse laser will propagate
- $\rho R \sim 2 \text{ g/cm}^2$

Peak Compression Profiles



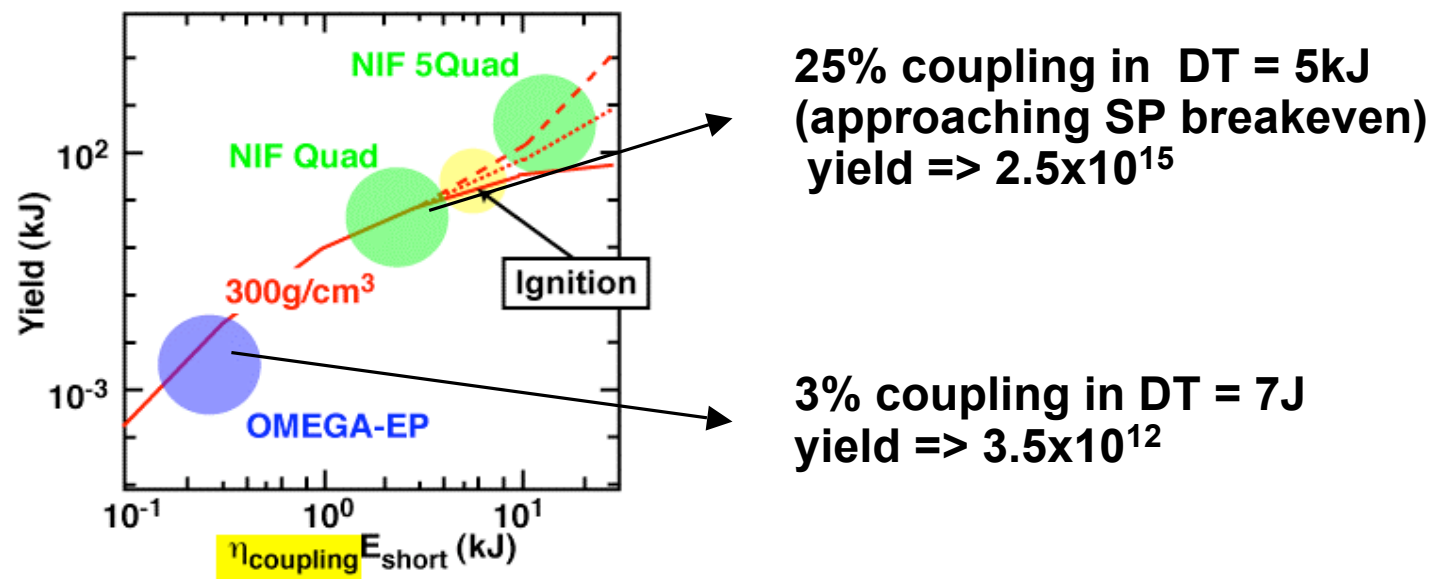
Full scale FI implosions on NIF will be optimized using the ARC Compton Radiography



- NIF ARC gives 4 snapshots in time from 2 orthogonal lines of sight
- 5 shots on NIF using the ARC in late FY09

Measuring neutron yield is a sensitive measure of coupling to the compressed core

Yield depends strongly on core temperature ($Y \propto T_{\text{ion}}^4$)
and is a powerful integrated measurement of coupling



NIF can measure:

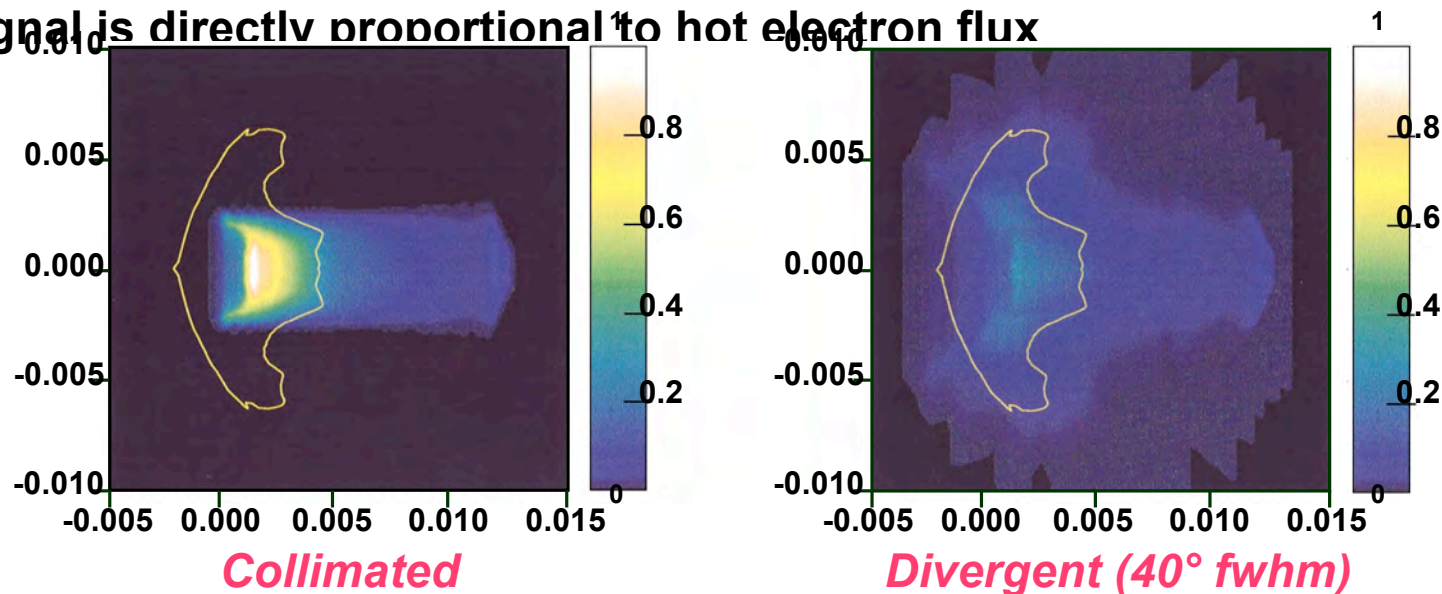
- DT neutron yields 1×10^{11} - 2×10^{19} and DD yields from 1×10^{10} - 5×10^{12}

Conclusion: NIF can measure coupling from few to >25% with existing diagnostics in both CD and Cryogenic DT targets

Fluorescent imaging diagnostic will show where hot electron energy was deposited

- Fluorescent imaging does not depend on target heating to produce signal

- Signal is directly proportional to hot electron flux



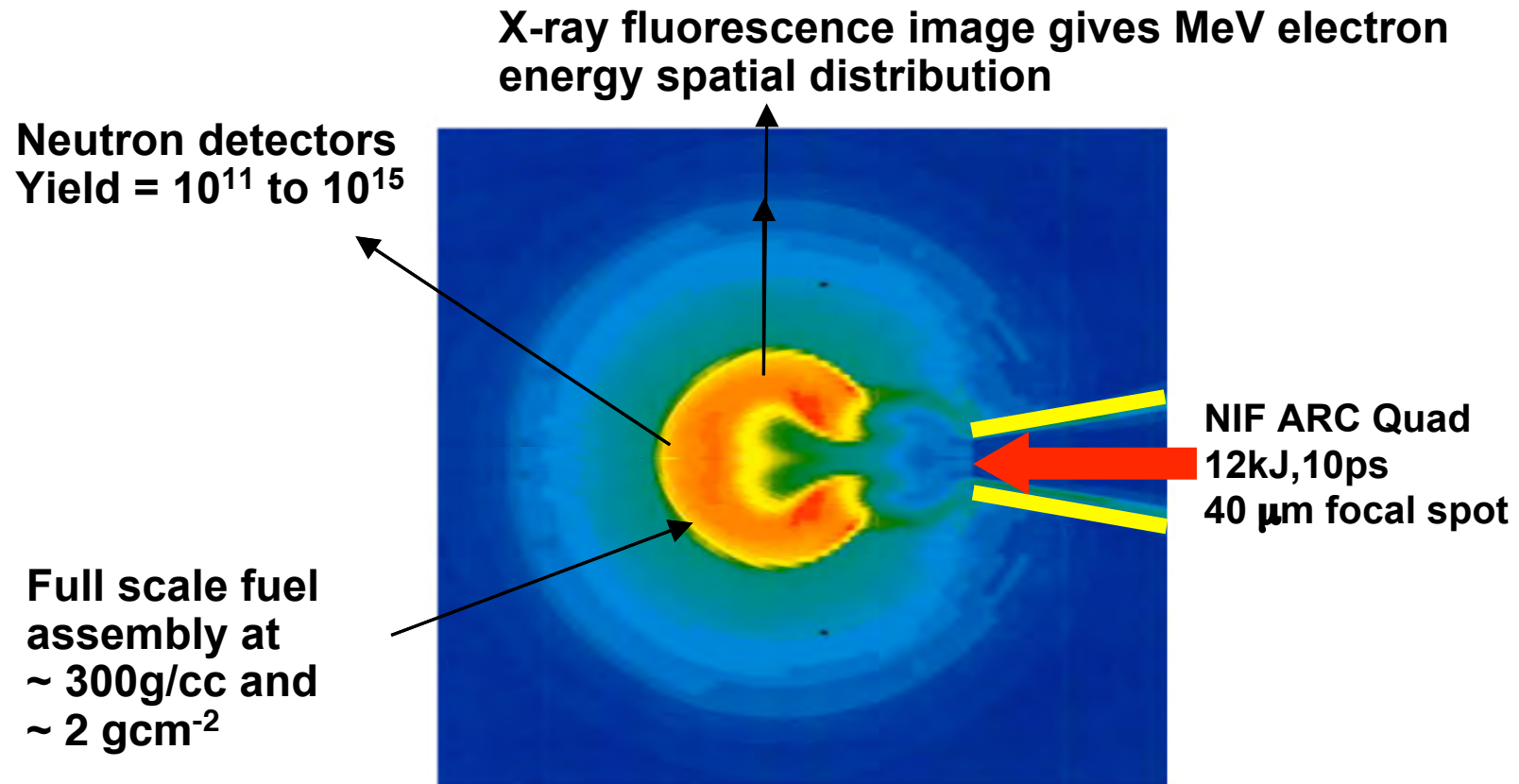
- Simulations show that fluorescent imaging is a sensitive measure of electron coupling to the core

**NIF high energy x-ray imaging diagnostic (HEXRI)
can perform this measurement**

The NIF campaign will provide the definitive Fast Ignition experiment



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- Coupling efficiency will benchmark our integrated design code
- This will specify short pulse laser requirements for high gain ignition

After 10 years, there are still no showstoppers apparent for Fast Ignition



- **Coupling efficiency appears adequate at 15–25%**
- **Lots of challenges remain**
 - **Improved implosion and ignition schemes**
 - **Reduce distance between critical high density**
 - **Improve efficiency of producing compressed core**
 - **Optimal energy deposition profile for short pulse**
 - **Develop detailed understanding of electron transport**
 - **Focus ion beams to high intensity and produce them with good efficiency**
 - **Understand scaling to high energy and long pulses**
 - **The capability for proof of principle experiments is at hand**